New Post-Construction Site Characterisation Models for Low-rise Buildings Founded on Highly Expansive Clays.

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DECLARATION

The candidate herein declares that the research presented in this thesis contains no material which has been accepted for the award of any other degree in any University or other institution. I affirm that to the best of my knowledge, this thesis contains no material previously published or written by another person, except where due reference is made in the text of this thesis.

Dominic Lopes

ABSTRACT

The city of Melbourne is the capital of the state of Victoria situated in the most southern part of the Eastern Australian mainland. The most recent Australian Bureau of Statistics (ABS) figures released in June 2017 show that it is now a city of 4.5 million people and growing at 150,000/year. In the past 3 decades ≈3.6 million houses and apartments were built in Australia of which almost one million were built in Melbourne. Approximately 70% of these dwellings (≈700,000) were unattached 1 to 2 storey houses, many of which were built on highly expansive basaltic clays in the outer suburbs.

In this same period the whole of the state of Victoria experienced, what the Australian Bureau of Meteorology (BoM) described as the 'Millennium' drought (Sometimes referred to as the 'Big Dry') which lasted from 1997-mid 2010 and was followed by the wettest consecutive 2 year period on record. From 2012 to mid-2016 an El Nino event caused a further drought followed by a short wet El Nina period commencing in mid-2016. These climatic events caused foundation movements which damaged many thousand homes.

Initially the 'Millennium' drought caused edge settlement due to clay shrinkage and edge heave (lift) after a very wet and sudden break of this drought. Approximately 5,000 of the houses from a total of ≈38,000 built in the area, between 2007 and 2012, were reported to have experienced significant 'slab edge' and/or 'corner lift' (i.e.: ≈12.5% of all houses built in this area during this time).

Some of these houses have been purchased by the builders and legal cases are still in progress. Similar and more serious drought and flood conditions have occurred in many other parts of the world resulting in expensive legal, repair and replacements costs. In housing the costs are said to be in many billions/year world-wide. Infrastructure repair costs (mainly for roads) are expected to be even greater.

The first Australian Standard (2870-1986) –'Residential Slabs and Footings', which attempted to address these problems, provided, what it termed, 'deemed-to-comply'

footing solutions. One of the main aims of this Standard was to limit the costs of footing construction on highly expansive soils, and does so, by making recommendations to the engineer, builder and owner on how to moderate the soil moisture conditions and construct footings to suit the conditions.

This thesis presents the results of 85 damaged houses investigated and several soil profiles and the Werribee volcanic plains. The data was sourced mainly between 2005 and 2016 and used to determine whether the existing Characterisation models have succeeded. Historical Thornthwaite Moisture Index values were examined also used to help predict future foundation ground movement and reduce house damage.

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I dedicate this thesis in remembrance of my parents and Dr Bartolo Parisi because without their love and guidance my life would have been greatly different.

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NOTATATIONS AND ABBREVIATIONS

AS2870:	Australian Standard – Residential slabs and footings.
AS1289:	Australian Standard – Methods for testing soils for engineering purposes.
AS1726:	Australian Standard – Geotechnical site investigations.
α:	Soil lateral and loading factor.
BoM:	Australian Bureau of Meteorology.
CCS:	Conditioned core shrinkage test.
Cs:	Conditioned suction.
Cw:	Conditioned moisture.
d:	Differential movement.
Δ:	Differential footing deflection.
Δu:	Soil suction change.
Δu_s:	Soil surface suction change.
Δw_s:	Change in surface moisture.
e:	Slab edge distance.
Gw:	Gravimetric moisture.
H:	Thickness of soil layer under consideration.
Σ:	Sum of soil layers
Hs:	Depth of design suction change.
I_{ps}:	Shrinkage or instability index without lateral restraint or loading of soil.
I_{pt}:	Instability index including lateral restraint or loading. (Pico-Farad - pF).
I_{ss}:	Shrink/swell index.
I_{sh}:	Shrink index.
N:	Number of soil layers within the design depth of suction change.
S/S:	Shrink/swell test.
SWCC:	Suction-water characteristic curve.
TMI:	Thornthwaite Moisture Index.
U_{eq}:	Depth of equilibrium suction.
Wf:	Edge distance.
y_m:	Differential mound movement.
y_s:	Characteristic surface movement.
z:	Depth from the finished ground level (in metre) to the centroid of the area defined by the suction change profile and the thickness of the soil layer being considered.

TERMINOLOGY

‘Deemed-to-comply’ footings: AS2870 Footings that meet the classification requirements.

‘Normal’ sites: Sites classified as A, S, M, H1, H2 or E in accordance with AS2870 and where foundation moisture variations are only seasonal or from regular climatic effects, effect of the building and subdivision, and normal garden conditions without ‘abnormal’ moisture conditions. However these sites can be expected to be adversely impacted by irregular climatic effects, which could include prolonged droughts.

‘Abnormal’ moisture condition: Where the foundation moisture variations beyond those of ‘normal’ sites. Building constructed on these sites have a higher probability of damage.

‘Covering’ soil: Lightly compacted soil placed against the exposed faces of the edge beams

‘Heave’: Swelling of foundation soil profile.

‘Lift: Slab curvature due to swelling soil profile.

CHAPTER 1
INTRODUCTION

1.1 INTRODUCTORY REMARKS.

This thesis has been written from research carried out by the author during a decade-long project investigating damaged houses and building practises. This work has benefited from the testing of many hundred houses built during chaotic climate conditions in the past 2 decades. The results from 85 of these houses built in the research area alone have been quoted in chapter 6 and Appendix 1 and 2. The main aim was to determine whether the slabs designed prior to these conditions have been adequate and what changes they may require for a repeat of such conditions. The Australian Standard – AS2870, "Residential slabs and footings" has been the main design method followed by the residential engineers. This standard was written during a long wet period and its suitability has been questioned for recent climate and expected future conditions. Recently many thousand homes have needed moderate to severe repairs which has cost the building industry many $ million dollars/year and has created a large and growing damaged house stock. Some statistics are quoted in later chapters.

Speaking about this problem Nelson and Miller (1992), Liu (1997) said:

"Expansive clay is widely distributed around the world and causes damage to light buildings, pavements and slopes in many countries; this damage is due to the strong soil-water interaction especially in the clayey layers closer to the surface".

This thesis outlines a research into this problem, discusses a number of gaps in the Classification (Characterisation) system being used in Australia and some of the building practises that have failed the consumer and the industry. The investigation period included 4 cycles of drought and flood that set climate records for the research area. The area investigated has had approximately 30% of the detached and low-rise house constructed in the city of Melbourne for the past 2 decades. Australian Bureau of Statistics (ABS) figures show that an average of 6,200 detached houses/year have been built in the research area during this period. The data collected and referenced for this thesis has shown that the site classifications and construction methods have underestimated the Characteristic Ground Movement (y_s) in a significant sample of these houses. These dwellings have been founded on shallow 'waffle' or 'raft slabs' (s-o-g) based on the AS2870 site classification method.

1.2 HYPOTHESIS.

The hypothesis for this thesis is that a new Characterisation models may be needed to cope with a wider range of soil moisture conditions during and post-construction and changes in climate in the design life of houses. The design life of houses with respect to their performance may also need reviewing in line with scientifically determined predictions of climate changes in various areas.

The area investigated is in climate zone 3 (Temperate as classified in AS2870) but the results may be interpolated for other climate zones and soil types by an investigation of the soil properties in other geographic and geological areas. It is also hoped that with a better understanding of clay behaviour and new characterisation models engineers may be able to more accurately measure the characteristic ground movement (y_s) and predict future ground movements more quickly and more economically than present methods.

1.3 RESEARCH AIMS.

The aim of the research is to improve the current AS2870 characterisation model in an effort to protect future building stock from damage that is caused by extreme (but possibly more common) weather conditions. Note however the basic model for the slab design is not changed. To achieve these aims the following is envisaged:

- Research into past climatic conditions and their effects on foundation movement.
- Literature review of the relevant site characterisation and testing criteria.
- Comparing the performance expected from Australian Standard AS2870 – "Residential Slabs and Footings" against the performance of 88 slabs investigated in the past decade.
- Examining and researching the y_s model parameters (Δu_s, H_s and u_{eq})
- Reviewing field and laboratory test methods used to determine y_s and y_m.
- Developing new design models to reduce house damage in future climate events.

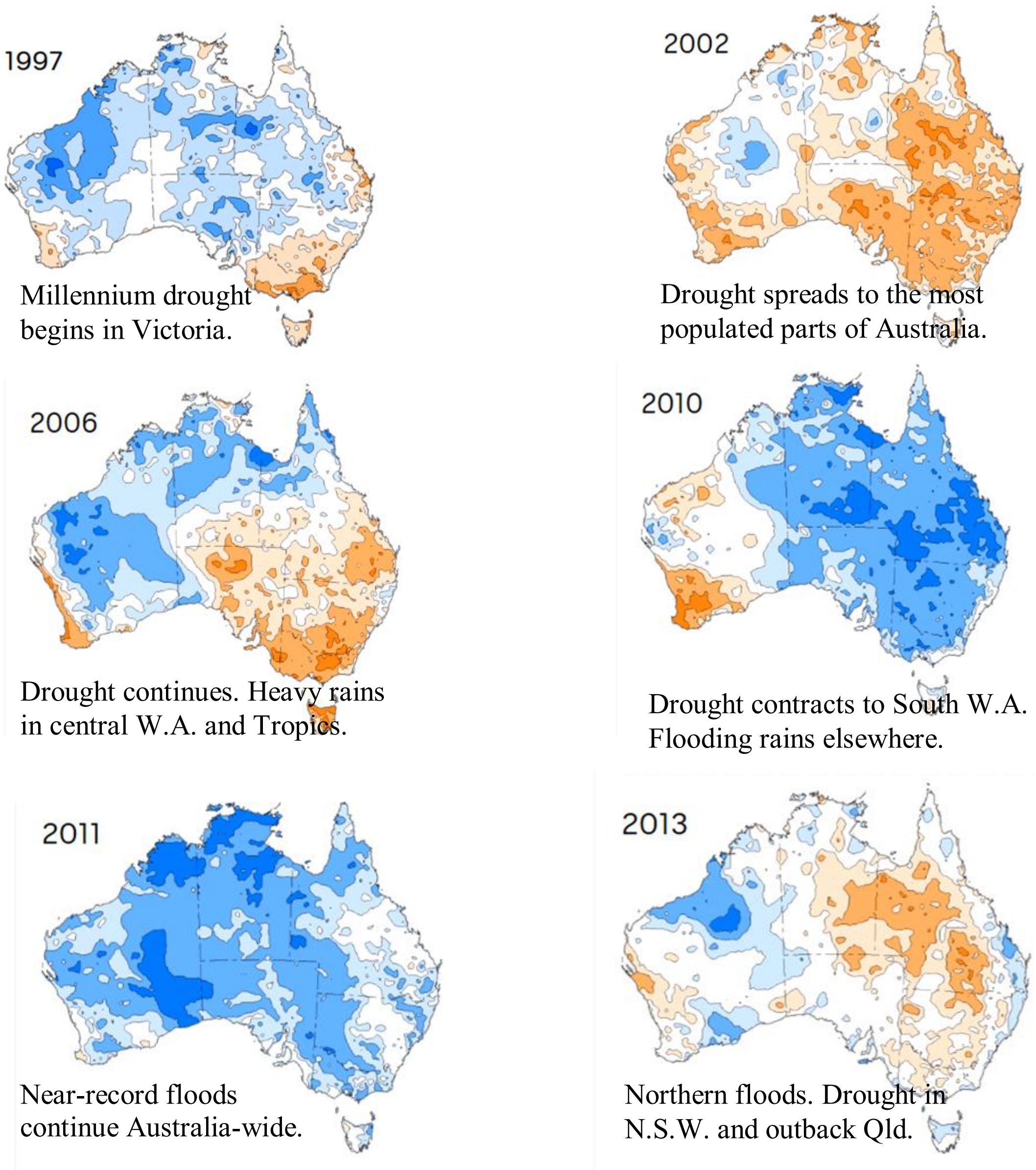
1.4 CONTEXTUAL INFORMATION.

The Australian method of characterisation of expansive soil sites for light structures, while being accepted for many years in practice, has not handled the behaviour of soils under extreme variations from drought to wet, such has occurred in recent times. It also has not satisfactorily addressed the variations in foundation soil moisture on building sites during and post-construction.

Australia has a wide distribution of expansive soils and some of the major cities have large areas with these soils. This thesis concentrates on such an area on the Western and Northern edge of Melbourne, Victoria, but the outcome has implications well beyond that region and in many other areas in other continents that have climatic extremes.

1.4.1 Chaotic Australian climate in past 3 decades.

Figures No 1 to 6 show the unprecedented chaotic climate that Australia has experienced in the past 3 decades which together with inadequate site characterisation, slab designs and poor building practises in the research area have caused considerable damage to many thousand houses.



Millennium drought begins in Victoria.

Drought spreads to the most populated parts of Australia.

Drought continues. Heavy rains in central W.A. and Tropics.

Drought contracts to South W.A. Flooding rains elsewhere.

Near-record floods continue Australia-wide.

Northern floods. Drought in N.S.W. and outback Qld.

Figures 1 to 6: - Australian chaotic climate in past 27 years (BoM web page).

1.4.2 Cracking soils in Victoria.

Most of the residential developments built on expansive soils in the eastern part of the continent and are derived from alkaline rock types that usually have had their Calcium leached and replaced with Sodium; leaving the clay particles with and excess of negatively charged particles.

The research area for this thesis is part of the basalt lava flows (Newer Volcanics) which occupy most of the western and northern suburbs of Melbourne, Geelong and the southern half of western Victoria. Other expansive clays are derived from weathered limestones in the west of Geelong and highly calcareous alluvial clays in the Murray River Valley Basin.

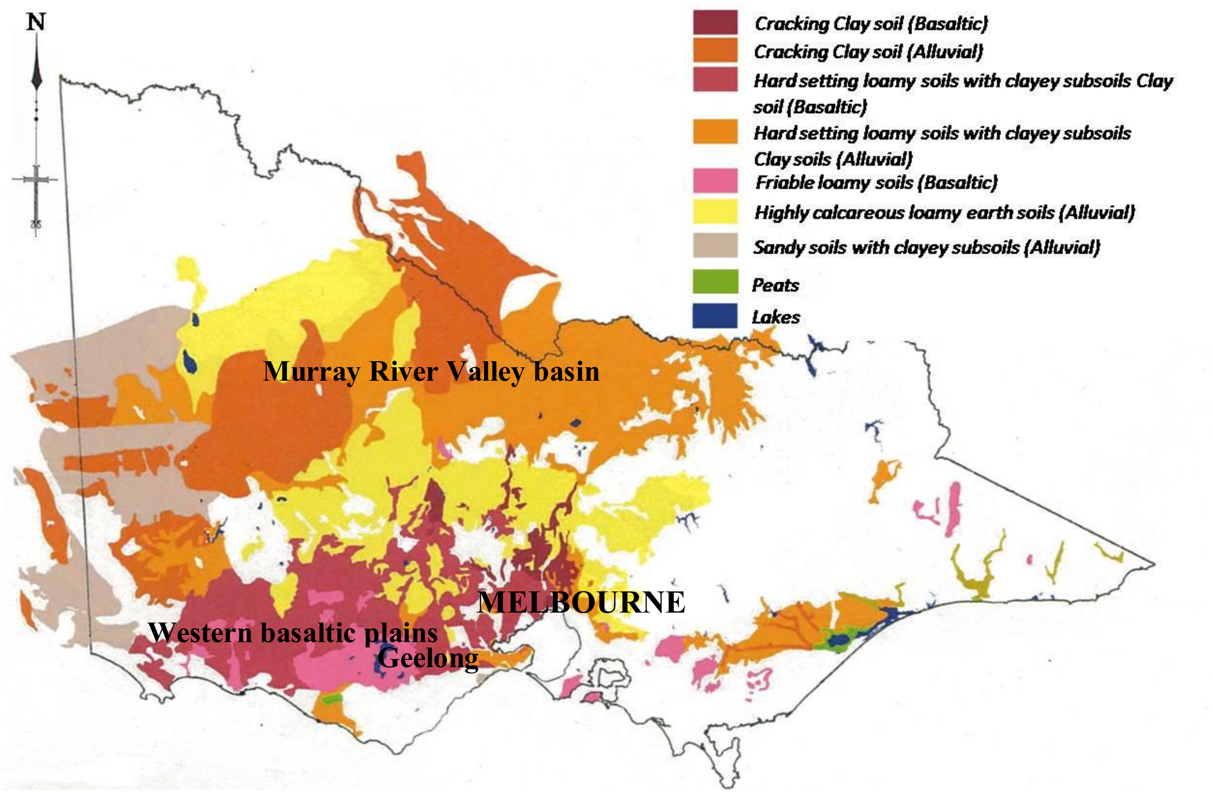


Figure 7: - Cracking soils in Victoria. After Holden, Lopes and De Marco (1995)

The research area was chosen because of the highly expansive soils, substantial increase of damage reported and recently experienced chaotic weather. It gave the author an opportunity to investigate the AS2870 'Characteristic Ground Model' (y_s) in these weather conditions. This area is generally covered by 0 to 5 metre depth of basaltic clay derived from Quaternary and Neogene age basalt lava and some aerially extruded, pyroclastic material, such as tuff and ash deposits which occupy about 1,500 km^2 in the state of Victoria and part of South Australia.

These volcanic deposits, are distinguished from the 'Older Volcanics' (Palaeogene age) which are regularly exposed in the east of Melbourne and on both sides of the Great Dividing Range which follows the east coast of Australia and parts of New Guinea for ≈3,000 km. Other highly expansive clays are found in many parts of Australia derived from the weathering of alkaline volcanism and calcareous sediments.

1.4.3 Climate setting in Melbourne.

Melbourne summers are hot with occasional heavy rain storms. Autumn is warm and dry. Winter and spring are cool with variable rainfall. In the research area (Werribee Plain) all seasons are windy and the mean rainfall is 536 mm/annum with ≈+/-25% variation. The mean, maximum and mean minimum annual temperatures is 19.7° day time and 9.3° night time averaged over 136 years, Bureau of Meteorology (BoM) on-line (2015).

The climate terminology for Site Characterisation used by AS2870 differs from that used by BoM and has been adopted for engineering purposes only. Using this terminology the research area is considered 'Temperate' and is based on the Thornthwaite Moisture Index (TMI) range of -5 to -15. The TMI was used to approximate some soil parameters to aid in site characterisation (locally referred as 'classification'. This basis was adopted by the Australian Standards Committee for the 1996 issue. Since then many researchers have published TMI state maps using slightly different calculation methods with moderately differing results.

Although TMI is a good guide to some of the model parameters used in AS2870, the author considers the soil moisture which develops during and post-construction to be even more important to predict future footing movements. Slabs built in very dry or very wet conditions have the potential to cause the largest slab curvature along the perimeter and corners of the slab. It is difficult for an engineer to design footings for soil conditions that may vary significantly at the time of construction and well after site classification and footing design. Any model for calculating the "characteristic mound movement" (y_s) would need to include a reasonably predictable variation of climatic conditions for the life of the house. In the past 3 decades the climate in Melbourne has been more chaotic that in the past, particularly in the western and northern suburbs where the soil is highly expansive.

1.5 THEORETICAL FRAME WORK.

1.5.1 Australian Standards slab designs.

An Australian Standard for residential footing construction was first published in 1986 specifically to address the up-coming problem of developing suburbs in expansive clay.

Walsh and Cameron (1997) gave particular credit to the influence of two early research activities reported to the Building Research Advisory Board (BRAB), (1968) and to Lytton (1970) from Texas University who worked in Australia for some time and retained his connections with the Australian engineering community.

Since 1986, AS2870 has been widely used for the standardisation of design of footings and slabs and to reduce the effects of foundation movement over the design life of houses (and similar sized, light industrial or commercial structures). This standard pays particular attention to designs for sites which have highly expansive soils. The 'classification' (method in this document guides the engineer in the design of footings and drainage systems with respect to the ground and slab movement. The footing designs recommended are either 'deemed-to-comply' (Section 3) or 'design by engineering principles' (Section 4) The former require a Site Classification to be made as outlined.

The main area of interest for this thesis is the pre and post-construction behaviour of lightly loaded structures built with shallow foundations founded on expansive soils and the modelling of ground movement. Figures 8, 9(a), (b) and (c) show the possible slab shapes and the relationship of 3 important design parameters, i.e.:

- Differential mound movement (y_m).
- Slab edge distance ('e')
- Slab span.

In the 1996 Australian Standard review 'waffle' slab designs were included and were considered to attain shapes similar to those in figures 8, 9 and 10.

1.5.2 Simplified beam on mound theory.

Walsh (1975) initially developed a mound model (Figure 8) from work by Lytton (1970) in Texas, USA which was later (1997) by Walsh and Mitchell to include 'edge lift' and other slab shapes (Figure 10).

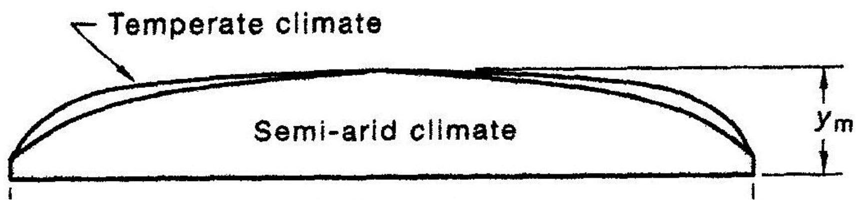


Figure 8: - Effect of climate on Mound-shape. (AS 2870-2011, Commentary).

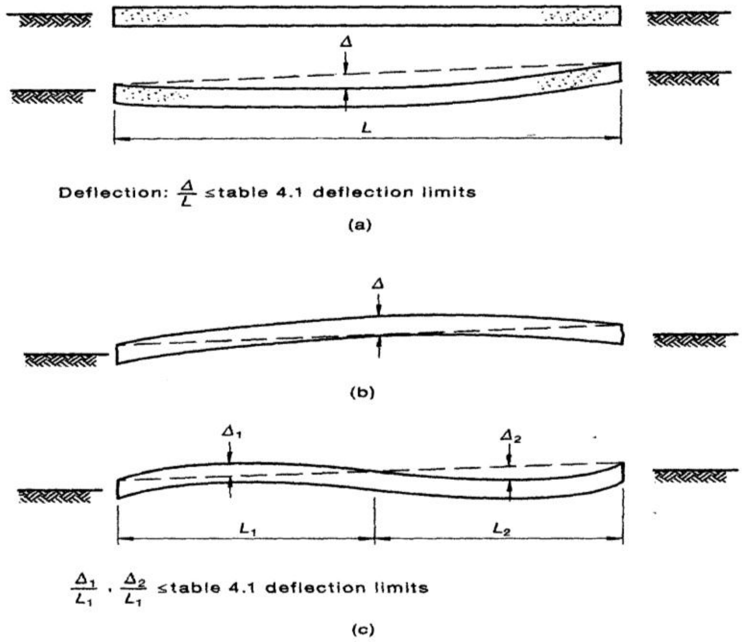


Figure 9(a), (b) and (c) Measurement of slab deflection (AS2870-2011-Commentary)

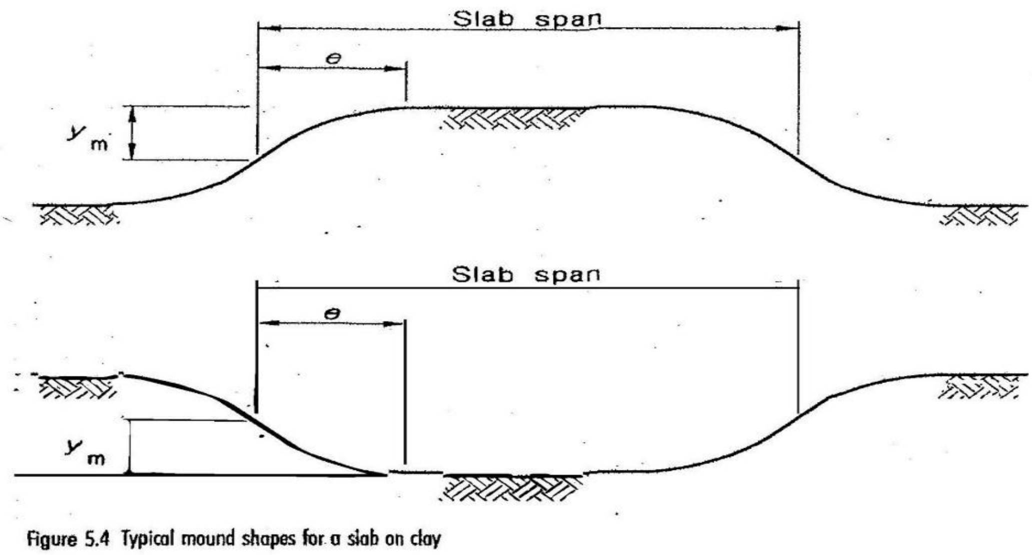


Figure 10: – Idealised ground movement patterns in clay sites (AS2870-2011)

In this thesis the author has pursued the problem of slab distortions with field and laboratory investigations of 85 house slabs and 36 sites. These investigations were conducted between 2005 and 2016 during 4 chaotic weather episodes recorded by BoM. The first of these periods was the 'Millennium' drought (most severe drought recorded) dating from 1997-to early 2010 followed by the 2 wettest consecutive years recorded in Melbourne in mid-2010 to early 2012, due to an El Nina event. This event was followed by an El Nino drought from 2013 to mid-2016 and a short, but very wet El Nina during the winter and spring of 2016.

In Australia, most detached houses are built of light construction (other than in areas subject to cyclones) and generally of one or two storey. Footings in the past 30 years have been mostly concrete ‘waffle’ slabs or ‘slab-on-ground’ (s-o-g) or ‘stiffened rafts’. More recently ‘waffle’ slabs have become the most popular, particularly with the larger building companies and the predominance of flat land in the developing areas.

The outer walls are mostly brick ‘veneer’ and do not support roof load in either slab types. This load is mostly supported by pre-fabricated timber trusses resting on timber or steel wall frames. The internal walls and ceilings are made of timber and mostly faced with dense plaster-composite sheets. This light construction, together with the beam configuration of the slabs, places very little load on the ground which accentuates the effect of clay swell.

Since soil moisture change occurs mostly in the upper soil layers, the engineering problems are more serious in infrastructure with shallow footings such as s-o-g, pavements, roads, pipelines etc. Figures 11 and 12 demonstrate the two most popular slab plans i.e. ‘waffle’ and s-o-g. In the research an almost equal number of slab types were investigated to establish whether there was any statistical difference in their performance.

The roof is made of composite cement tiles or corrugated ‘colour bond’ steel sheets. Most houses have lightly reinforced ‘waffle’ slabs, (Figure 11) which are built above ground with polystyrene ‘pod’ form work. Those with s-o-g concrete floors have excavated trenches to accommodate the beams, (Figure 12). Both of these slabs are constructed monolithically with internal and external concrete beams which vary in depth depending on the site y_s.

1.5.3 Typical slabs constructed in the research area.

Waffle slabs.

There are 8 design groups for these slabs based on the site classification and 2 to 4 types in each group based on the structure type.

The concrete beam depth varies from 260–610 mm and their width from 300–110 mm, depending on the combination of the above site classifications and structure type.

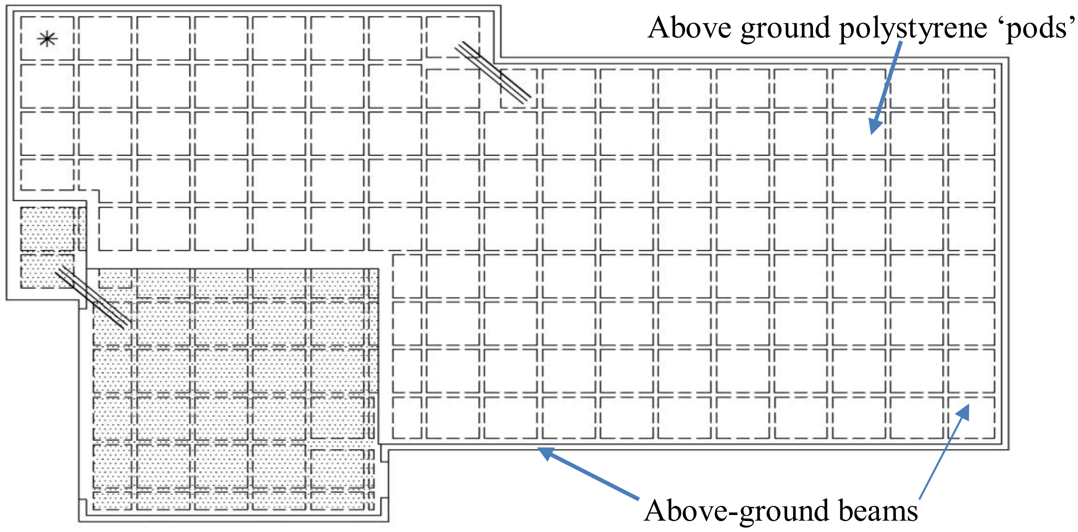


Figure 11: - Typical 'waffle' slab.

The reinforcement for the beams and slab also varies according to classification and structure. In some cases this slab can be supported by piers provided additional N12 bars are added to the top where internal beams intersect piers. The site is dug flat with or without shallow fill. A vapour barrier sheet is placed under the slab and the slab constructed above ground.

Slabs-on ground

These slabs(s-o-g) are monolithic and dependent on Classification and structure type. The beams are all 300mm wide and vary in depth from 300mm to 1,000mm and founded in excavated trenches. The beam spacing and slab and beam reinforcement varies according to Classification and structure type. If a site cannot be classified both 'waffle' and s-o-g require an individual engineering design or design by the engineering principles in Section 4, AS2870.

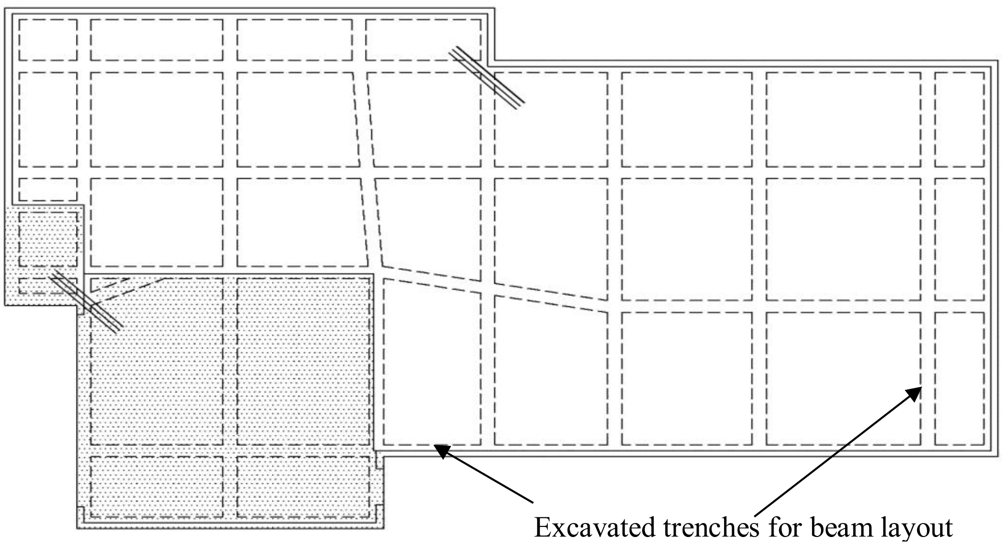


Figure 12: - Typical 'slab-on-ground'.

1.6 EXTENT OF THE PROBLEM.

1.6.1 The international scene.

The recent close repetition of droughts and wet periods has caused severe differential ground movements under roads, houses and light infrastructure founded on expansive clays. This research has concentrated on new residential houses built on such soils in the Western and Northern Melbourne suburbs, however the findings have world-wide relevance wherever infrastructure with shallow footings is founded on highly expansive soils. The cost of construction and repairs are very high and often overlooked in the planning and construction stages. A number of researchers have attempted to estimate these costs.

According to Scott (1974) the estimated damage repair costs to structures and pavements in First World countries alone from the 1972 El Nino was $4 to $5 billion. As a result of the world-wide El Nino in Australia in the early 1980's the repair costs of infrastructure increased considerably. Nelson and Miller (1992) noted that expansive clay is widely distributed and was causing damage to light buildings, pavements and slopes in many parts of the world. In Britain the insurance claims for residences (only attributed to foundation shrinkage) reached $1 billion in 1995. The following year these claims almost doubled, driven by tree drying in a severe drought and a change to more lenient insurance claim requirements, Driscoll, Crilly and Butcher (1996)

Li and Cameron (2002) reported:

"The cost of repair of the infrastructure in Australia, China, India, South Africa, U.K, China and U.S.A. are annually very high. In China and U.S.A. alone it was estimated to be in excess of $30 billion".

Al-Rawas and Goosen (2006*)* commented on costs of clay expansion:

"It is a world-wide problem and the repair costs are estimated to exceed $15 billion/annum in the United States alone".

1.6.2 The local scene.

In 2005 The Allen Consulting Group Carried out a desk-top survey of the costs of disputes in the residential and commercial sector in Victoria at the request of the Victorian Building Commission (VBC). They found that the average cost of disputes in the residential sector were approximately:

(a) Minor conflicts: $ 4,813 each. (Generally dealt by the builder only)

(b) Disagreements: – $ 8,058 each. (Dealt by builder and consultant)

(c) Disputes: - $ 110,297 each. (Included builder, experts and occasionally lawyers)

From this report the VBC estimated that the cost to Victorians for building disputation was (at the time) over $500 million/year.

Mills, Love and Williams (2009) reported on a desk-top survey from Housing Guarantee Fund Limited (HGFL) records, which contained over 800,000 properties resulting in 110,000 claims from all houses built from 1982-1997 (≈14%). Most of these claims however were about damage due to poor plumbing, bathroom fittings and footing construction. A sub-set of 32,000 properties with complete information were chosen and these showed that the remedial costs represented an average of 4% of their contract value.

The Australian Bureau of Statistics (ABS) figures between 2001 and 2015 showed that 93,000 (Approximately 6,200/year) new detached houses were built in the suburbs being investigated. Personal experience is that almost all are being built on highly expansive basaltic clays.

In 2011 the Victorian Building Authority (VBA) commissioned ‘Meinhardt’ to carry out a desk-top survey of the slab-lift problems from 20 major builders however only 7 of these builders responded. In this report 625 slabs were ‘desk-audited’ and their builders stated that 32 newly built houses have significant structural problems (>5% of those constructed by the responding builders). The poor response to the survey is likely to have been influenced by the fact that the largest builder was already in legal cases and many others were receiving bad publicity.

In 2012 the Victorian branch of the Australian Housing Industry Association (AHIA) reported to the industry that there *were approximately 4,500 houses with slab-lift problems built in the previous 6 years.* (≈750/year). Based on this figure the number of reported ‘problem’ houses represent ≈12% of the houses built.

The local industry and its professional practitioners involved in forensic work generally agree that this situation has come about by the following combination of events and conditions (Personal communications):

- Longest and most severe drought on record.
- Wettest consecutive 2 year period immediately after this drought.
- Site conditions not within the ‘deemed-to-comply designs’ scope of AS2870.

- Slabs designed and constructed to 'normal' site conditions.
- Miss-understanding of the AS2870 requirements.

Being able to calculate changes in foundation conditions and the effects of climate on ground movements and devising economical and effective solutions to deal with them, would minimize damage, disputation and save resources. Since the moisture change usually occurs in the upper soil layers the resultant engineering problems are only experienced by structures with shallow footings, slabs-on-ground, pavements, pipelines and roads.

1.7 SUMMARY OF METHODOLOGY OF RESEARCH.

To achieve its aims of determining the pre and post construction causes of house damage, this thesis has researched the following:

- The parameters used to calculate y_s per Australian Standard 2870.
- Investigation of 85 houses carried out by the author and 'USL Group', 'JM Fieldwork' and 'Structural Works' to determine the slab performance and dilapidation causes.
- Development of a new shrink/suction test to eliminate some of the issues in the existing testing to determine the Instability indices,
- Comparing calculated y_s with y_m and slab deflections.
- Assessing the processes that have an effect on the slab performance.

1.8 PLAN FOR THESIS.

Chapter 1 - Introduction

Chapter 2 - Literature review

Chapter 3 – Characterisation of expansive clay sites.

Chapter 4 - Design and pre and post construction issues.

Chapter 5 – Laboratory and field investigations.

Chapter 6 – House investigation results.

Chapter 7 - New design models.

Chapter 8 - Concluding remarks and recommendations.

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CHAPTER 2
LITERATURE REVIEW

2.1 HISTORICAL PERSPECTIVE.

Through the work of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and many other state and federal science and construction organisations, Australia has undertaken a great deal of research into soil and engineering particularly in response to WW1 and for WW2 defence needs. Extensive soil and geological mapping began in the 1920's for farming and mineral exploration and soil classification systems have been used in Australia since Prescott (1920). In the 1950's and 1960's Hallsworth, Leeper and Northcote, et al., continued to extend the knowledge. One of the first Australian maps linking soil types and landforms (Figure 13) was produced by Stephens in (1961).

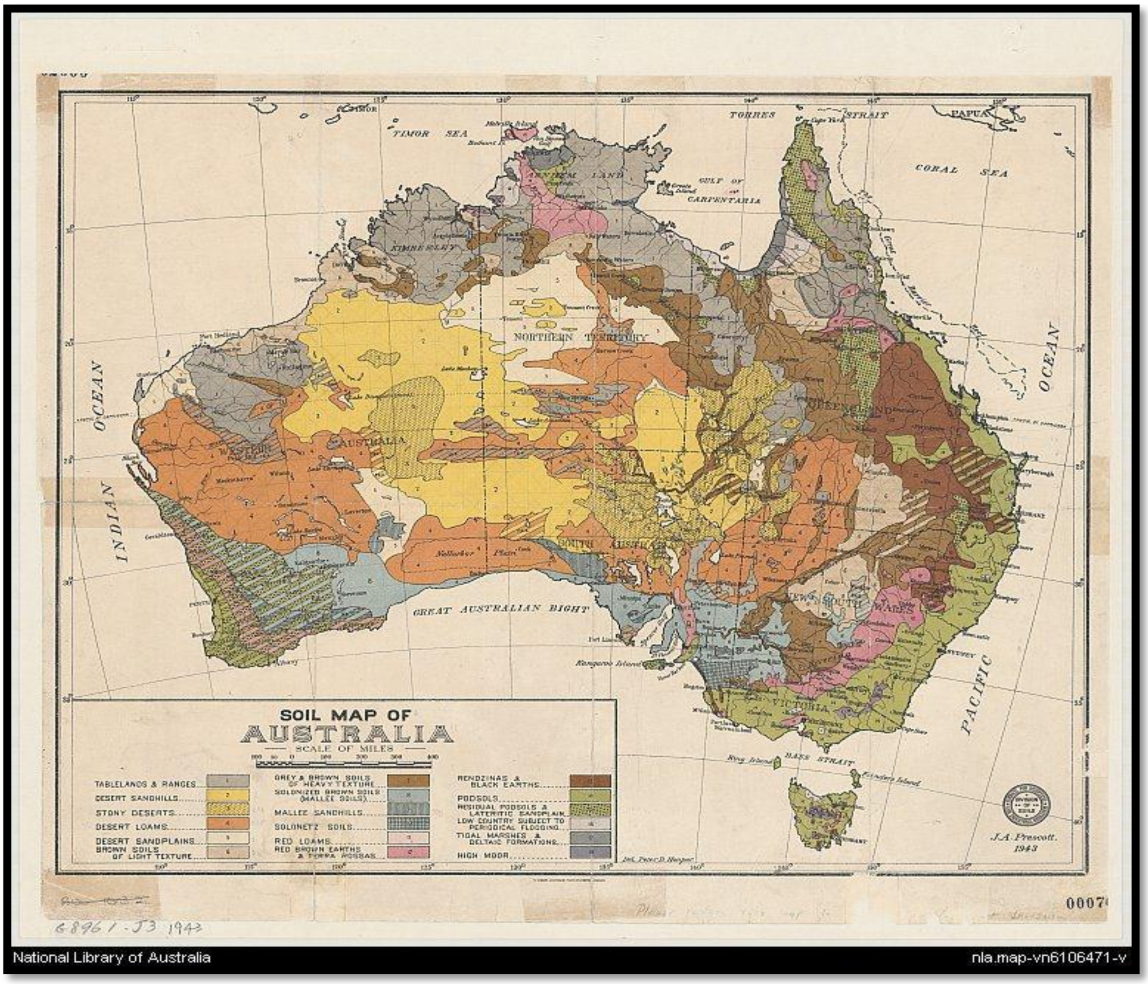

Figure 13: – Soil map of Australia linking soil types and landform (Stephens, 1961)

CSIRO published a number of technical papers by Grant (1972-1973) concerning the Terrain Classification and evaluation for engineering purposes of the Melbourne and nearby areas.

From the 1960's onwards the effect of expansive soils came out of the laboratory and into the field. From the late 70's the movement of these soils was considered a significant problem, particularly for road and shallow footing construction. At this time the cost of the poor performance of shallow footings on expansive clay gained the attention of researchers, particularly in CSIRO.

Expansive clay areas cover approximately 20% of the Australian continent. All major cities other than central Sydney and central Perth have such soils. Recently many new suburbs in Adelaide, Melbourne and Brisbane and to a much lesser extent in outer S.W. Sydney have been built on these soil types.

2.2 GEOLOGY AND SOIL TYPES IN THE RESEARCH AREA.

The research area occupies the western and northern suburbs of Melbourne including the Werribee Plains, which is now the largest growth area of Melbourne. This thesis centres on clays derived from Quaternary and Neogene age basaltic lava (locally known as Newer Volcanics) which sometimes includes aerially extruded pyroclastic material.

The basaltic clays North and East of Melbourne (known as the Older Volcanics) were extruded during the Palaeogene period. These clays are generally expansive than those from the younger extrusions and often have more iron content.

Most of the minerals in the 'Newer Volcanics' in Victoria are composed of alumina silicates with varying amounts of other minerals and salts. The predominant mineral constituents are olivine, plagioclase feldspar, clinopyroxine oxides and volcanic glass.

Isbell (1992), described the process of weathering of the 'Newer Volcanics' in this way:

"The infiltration of rain water (weak carbonic acid) dissolves the carbonate from the secondary minerals in the basalt to form a solution of calcium bicarbonate. The solution is held by capillarity until it evaporates and then the calcium carbonate is precipitated".

The basaltic clays in the research area are partly fine crystalline, extrusive with a glassy matrix which have weathered to a mixture of Montmorillonites, Smectites, Halloysites and Kaolinites and often contain some Alluvial or Aeolian sand, silt and clay.

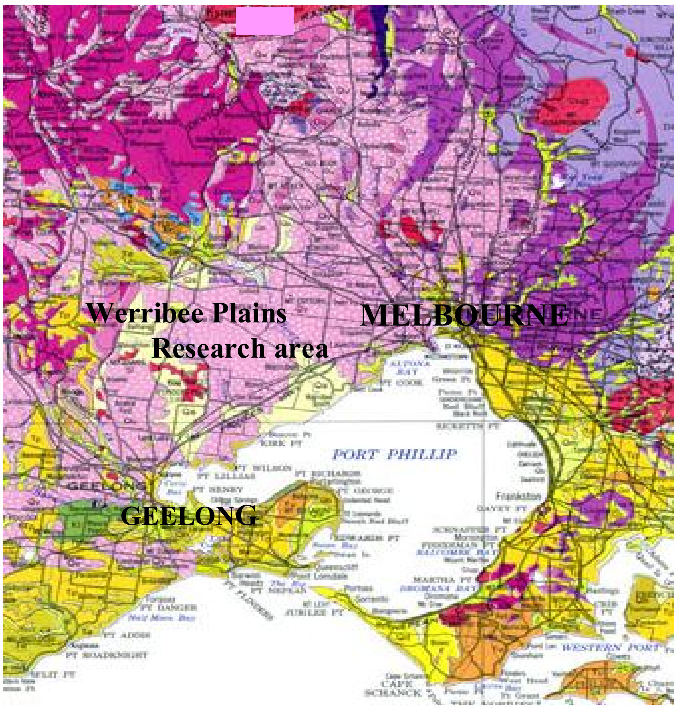

Figure 14: - Geology of research area (Werribee Plains – Neogene basalts.

In other areas in Victoria similarly highly expansive clays have been produced from limestones and other Calcium-rich volcanic, sedimentary rocks or river sediments.

Dahlhaus and O'Rourke (1992) in describing the weathering process stated:

"Olivine and pyroxene weather directly to a trioctahedral type of Montmorillonite and to iron oxides such as goethite and haematite. Plagioclase alters initially to an alumina Montmorillonite but can degenerate to Halloysite, Kaolinite and poorly crystalline Montmorillonite. In certain weathering conditions Montmorillonites can also be formed from other clays"

Nelson et al (2015) writing about the shrinking and swelling of clay wrote:

"The clay mineral particle together with its surrounding positive cations and water of hydration attached is held closely to the mineral core. Montmorillonite clays are weakly bonded and highly susceptible to cation substitution; they have a large number of voids, and many more spaces in the micelles which allow a greater amount of water to enter and exit the structure".

An important chemical change in the weathering common to Calcium-rich rocks is the leaching of Ca^{++} which, in basaltic clays, forms light coloured carbonate deposits, often referred-to as 'Calcrete'. This deposit can form as nodules, rock coating or soil layers where the soil water carrying dissolved Calcium intersects higher pH material (≥5 pH).

The leached Ca^{++} is usually replaced by Na^{+} leaving a residual negative charge on the surface of the clay platelets. This electrical imbalance causes the clay structure to open due to the weakening of the bonding forces and the incoming water continues this expansion by hydrating the cations. This is often called the 'wedge effect'. A larger particle surface is exposed and the water is imbibed both in the micelles and structural voids. The calcrete content is most important in basaltic clays because it lowers the Soil Index considerably**.**

Dahlhaus and O'Rourke (1992) showed the most common chemical change in the weathering of the Newer Volcanics by equation 1, which explains the leaching of the Calcium by mildly acidic ground water.

$$Ca\ (HCO_3)_2 = CaCo_3 + CO_2 \text{..} \textbf{Equation 1}$$

Describing the variations of swelling and shrinking of these types of clay, Nelson (2015), quoted Benson and Meer (2009):

"Clays having abundant monovalent cations have a much higher swell index than those with an abundance of divalent cations". "The amount of shrinkage may not equal the amount of swelling, depending on the nature of the cations and their hydration energy".

This last statement has particular relevancy to the Australian shrink/swell test. (Chapter.5)
The specific surface area of clay particles is an indicator of their expansive nature and cation-exchange capacity. Montmorillonite clay platelets are extremely thin and sometimes only a few atoms thick. (Refer figure 15)

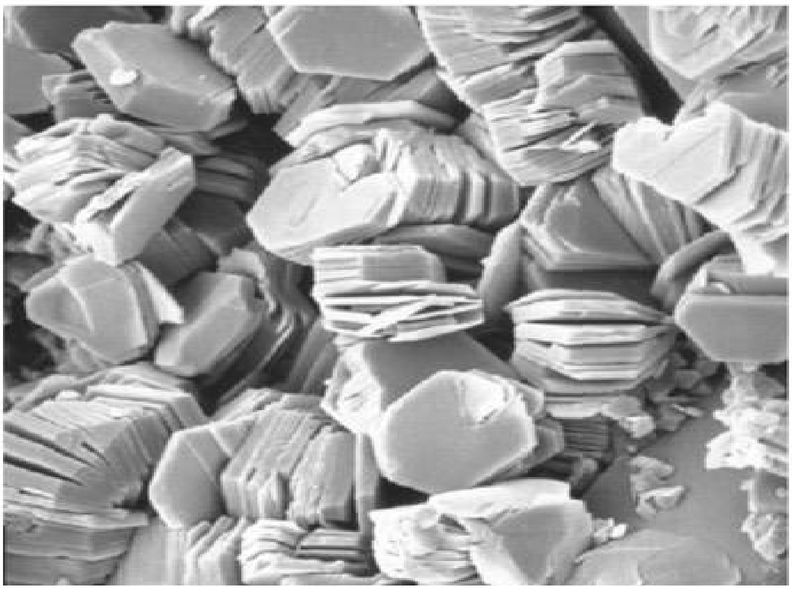

Figure 15: Typical electron micrograph of sodic clay aggregates. (Menzies et al, 2015)

Mitchell and Soga (2005) also highlight the importance of the platelet surface area with respect to cation exchange capacity in Table 1.

Table 1: Cation exchange capacity, Mitchell and Soga (2005)

Clay mineral	Cation exchange capacity	Specific Surface area
Kaolinite	1 – 6 meq/100g	5 - 55 m^2/g.
Illite	15 – 50 meq/100g	80 - 120 m^2/g.
Montmorillonite	80 – 150 meq/100g	600 - 800 m^2/g.

Lamb and Whitman (1969) speaking about the growth of Sodium ions say:

"Going from an un-hydrated state to a fully hydrated state this ion grows in size by more than sevenfold. If the hydration of the cations were to cause even 10% increase in the diameter of the cations this would represent a 10% change in the spacing between particles, which would correlate to a significant amount of soil expansion".

The weathering of the basaltic rocks in the research area have formed clays with high calcium (Ca^{++}) content, most of which has been leached and replaced by Sodium (Na^{+}), creating clay particles which lose many of their cations. The calcium forms white to grey calcrete deposits which are leached downwards in the profile and commonly form distinct layers or coats core stones or the surface of the rock. It can also form nodules in the higher pH soil layers and fills cracks in the clay. A similar process occurs when dissolved ferrous cations create nodules locally called 'buckshot gravel'. In some cases the Calcium, Ferrous ions and Aeolian soil particles join to form a weakly bonded 'ferricrete' layers.

2.3 SLAB DESIGN THEORY & SITE CHARACTERISATION.

Much of the house construction research of Australia was carried out by the CSIRO and other Government organisations and particularly by Aitchison, Richards, Lytton, Walsh et al in the 1970's and 80's and continued to this day by many other researchers. Thorne (1984) was instrumental in developing an Australian shrink/swell test method using a combination of shrink and swell tests without the need for suction readings. This test is becoming more popular with geotechnical engineers and is discussed later in this thesis.

Walsh (1974, 1975) popularised 4 slab designs through technical papers and other publications published by the CSIRO. At about the same time Holland et al also wrote a number of reports and papers showing 3 slightly lighter slab designs known as 'Swinburne type 1, 2 and 3'.

The Cement and Concrete Association (CCA) published a booklet written by Walsh, Holland and Kouzmin (1976) which preceded the Victorian Building Regulations published in 1979. This work together with the development of a large tract of flat land in the newer suburbs changed the footings for houses from mainly 'strips and stumps' to slabs-on-ground.

The first Australia-wide Footing Standard (AS2870) was published in 1986. Since then there have been major reviews in 1988, 1996 and 2011. In the latest review the slab designs for highly expansive clays were upgraded. This change was most timely since the large developments in the West and North of Melbourne, South-West Brisbane, Ipswich, Toowoomba, and the Darling Downs occurred in the basaltic clays.

Walsh and Cameron, (1997) published a handbook from a series of lectures describing some of the background to AS2870.

"In Australia, residential footings founded in natural soils rarely fail by excessive settlement or collapse. The common failure mode is swelling and shrinking of a clay soil due to moisture changes. The amount of vertical movement at the surface in Australian clay will generally be 10–100 mm, with most soils moving at the lower range. However in some areas larger movements are common".

The findings in this thesis have shown that a combination of weather conditions and building practices that do not follow all the strict requirements in AS2870 have led to greater ground movements.

2.3.1 Mound heave (centre lift)

Initially the Australian slab design was based on 'mound heave' (centre lift) and this was expected to be the long-term shape and best design model. Improved models were later developed by Walsh and Mitchell and entered in the Australian Footing Standard (AS2870).

The author's experience is that true mound lift in Melbourne climatic conditions have been very rare in the past 3 decades and only found where plumbing or badly constructed trenches allow water to ingress under the slab. Other reasons preventing a true centre lift shape may be:

- Water ingress to the centre of a house slab by clay suction requires a long wet period which has not occurred in the recent past.
- Water diffusion in the highly cracked soil column reduces the accumulation of water in the surficial layers directly under the house slabs. Judging from the slab shapes and

contours found during this thesis this moisture spread may only be around 3-4m from the edge.

- Each time the climatic conditions reverse the slab shapes changes and if the transitional period is short after a wet period the process of centre heave is reversed and if a drought follows, the edge of the slab returns to a concave shape.
- In some climates however there may be an accumulation of centre lift over many years.

AS2870 advises about any work that may change the site soil suction and void the Classification made prior to construction. e.g.:

- Site preparation and excavations or filling may change the moisture and structural integrity of the foundation soil and hence the Site Classification.
- Many parts of the construction process have the potential to change moisture condition of the foundation soil and increase the surface suction variation (Δu_s)
- The home owners can also have a significant effect on site moisture during landscaping, excavating for pools and various water discharges or plantings.

2.3.2 The as-constructed foundation moisture.

TMI in an area can alter the ’active depth’ of the soil moisture and suction and therefore may affect the classification of a site. The latest AS2870-2011 suggests that the TMI of a building area should be calculated using a minimum of 25 year TMI results. The TMI is based on past average and may be useful in determining the average depth of moisture change (H_s) however it tells us very little about future climatic conditions.

Figures 16(a) and (b) show the effects on ground movement under a slab which experiences different soil moisture conditions in its life. The strain in the relevant suction change is much lower in drought periods than in wet periods. (Refer Appendix 5).

Figure 16(a) shows that a house built in benign soil moisture conditions will experience a surface suction variation of ≈1.2pF and the slab distortion (y_m) will be roughly equal in both directions. However a slab built in drought conditions followed by flood will have considerable ‘edge-lift’. Figure 16(b).

Although in some cases a mound shaped slab may develop in natural conditions by lateral moisture ingress under the slab; settlement or lifting of the edge are much more common. Edge-lift is also usually more severe since the suction/strain trend line is steeper in the suctions between 4 and 3pF than where it is >4pF. In some cases osmotic suction also affects this relationship at the lower suctions.

2.3.3 Site development.

The initial site levelling work may be a major cause of post-construction ground movement. This cause is difficult to avoid after construction. During the initial subdivisional development in most of the research area the ground level of the allotments are made only slightly higher with the road gutter and the pipe grade cannot allow an effective flow. Even though weather conditions are the most common cause of clay shrinking and swelling, the pondage of water, drought drying and lack of garden maintenance are also important causes.

Drains emerging from under the slab are often dug level with the ground, allowing back-flow after the swelling of the soil surrounding the house has caused a negative slope. A common poor practice is to dig the trenches level in clay sites and then creating a very minor slope in the trenches by placing 7 mm ø crushed rock at varying levels. This method causes water to pond in the level or negatively sloped trenches and flow backwards under the slab. In some cases this water flows under the slab and to the kitchen, which is often placed in the centre of the house. To avoid this AS2870 recommends compacting a ‘clay plug’ around the pipes where they exit the slab. In the author’s experience in the slab investigations quoted here this advice has been rarely followed and is one of the causes of poor drainage.

There are several empirical equations that have been proposed to describe the SWCC curve e.g.: Sillers et al (2001):

“Some of the commonly used SWCC equations take the form of a continuous function that is asymptotic at the extremities. It is the zones between the air-entry value and residual suction: where the curve has sufficient slope for the calculation of soil suction. The same limitation applies when the SWCC equations have been inverted to solve for soil suction as the dependent variable”…”The same limitation applies when the SWCC equations have been inverted to solve for soil suction as the dependent variable”.

Recent climatic influences and a long residential building boom has led to design and construction practises that have caused an increasing cost for the industry and home owners due to poor house performance Australia wide. To determine more accurate characterisation model parameters to determine the causes of damage the author has reviewed the geological setting, rock weathering processes, clay composition and clay structural behaviour in the following chapter 2.

2.4 CLIMATE, SOIL & STRUCTURAL EFFECTS

In 1992 the AS2870 committee began to address the issue of climate and drew attention to its effects in the 1996 review by publishing a slightly modified TMI map for Victoria. More recently a number of researchers have published several papers and maps relating to soil suction, TMI, depth of design suction change (H_s) and Site Characterisation (y_s).

Damage caused by expansive soils is closely related to climatic effects. During dry seasons evapotranspiration causes loss of water in the shallow soil layers which increases the soil suction and is accompanied by shrinking and cracking of clayey soils. During wet seasons, rainfall infiltrates the soil cracks and decreases soil suction, which, in turn, causes the reduction of shear strength and swelling of these soils.

In hot wind-blown plains soil cracks are partly-filled with sand, silt and clay. During rain periods water also infiltrates these cracks which causes them to close by swelling; the greater proportion occurring laterally. When the lateral swelling is complete the vertical swelling begins to dominate hence α factor is >1 in the uncracked zone but 1 in the cracked zone.

This process also affects the behaviour of added compacted soil. In over-compacted surface clay and in the clay below the cracked zone the vertical swell is greater due to the lack of these soil cracks. The higher soil load at depth also reduces the vertical swelling. The soil restraint in the deeper soil and in new, highly compacted clay fill (even that sourced from the construction site) allows most of the swell to be vertical rather than partly lateral as occurs in the cracked soil. This effect has been considered in AS2870 by introducing the soil restraint factor (α) and formula. (Equation 6.) This soil parameter has been generally accepted however it may require closer scrutiny especially for the surface fill which can have a strong influence on the Classification.

2.4.1 New problematic building conditions.

In reviewing past literature and field conditions on the subject of ground movement, the author found that 'deemed-to-comply footings' were not suited to the climatic conditions experienced in the past 2 decades.

During a long drought, named by the Australian Bureau of Meteorology (BoM) as the 'Millennium' drought lasting from 1997 to mid-2010, the new house slabs experienced edge and corner settlement due to clay shrinkage. This drought brought on very strict water restrictions a deficiency of garden watering.

In the state of Victoria this drought was followed by a very wet El Nina event from mid-2009 to 2011, resulting in a significant slab shape reversal causing edge and corner lift. This wet period was then followed by another less severe drought between mid-2014 to mid-2016 which was again followed by a wet El Nina period. Within these time periods most of Australia experienced similar conditions.

2.4.2 Modern housing construction in the research area.

Most Australian houses are built of light construction (other than in areas subject to cyclones) and generally of one or two storey. In modern houses the outer walls are mostly lightly reinforced single brick acting merely as a 'veneer' and do not support the roof. The roof load is supported by pre-fabricated trusses resting on an internal timber frame. The internal walls are usually faced with a plaster/paper composite. This light construction, together with the beam configuration of the slabs. Settlements mostly occur in droughts due to clay shrinkage. . Very few houses are being built with double brick walls (full masonry) on expansive soil. (The standard has higher construction and design requirements for more brittle structures). The two most common slab-types (waffle or s-o-g) have a system of orthogonal beams. Waffle slabs are founded on the surface, on top of a moderately compacted 'pad' which often has some levelling fill. The beams for the s-o-g are founded below the surface at a depth of 300-500 mm but in some cases these beams are deepened if the presence of poor soil requires it. Waffle slabs have become the most popular, particularly with the larger building companies due to the predominance of flat land in the developing areas and their lower overall cost.

Due to a confluence of climate conditions, poor design and construction practices, some parts of Australia have recently experienced a significant increase of footing movement. The western and northern suburbs of Melbourne, in particular, have had severe foundation soil swelling conditions due to these factors and slab designs that did not anticipate the effects of the severe climate events. The drought years recorded 25% below the long term average rainfall.

On the matter of moisture and swell Sorochan (1991) noted:

"When the soil structure is disturbed, the internal irreversible bonds, which inhibit its swelling, are practically destroyed. Hence specimens of soil with an undisturbed structure swell to a less extent compared to those with a disturbed structure"

The core samples tested in this thesis (Chapter 5) were 'undisturbed' and not troubled by hysteresis. The shrink samples were measured with Vernier callipers and the suction with a dew-point mirror psychrometer. The test samples for shrink, moisture and suction testing reported here were collected by JM Fieldwork using a small hydraulic drilling rig pushing

> 38 mm ø x 300 mm long 'Shelby' thin-walled tubes. They were labelled, sealed and transported to the Swinburne University soil laboratory.

The surficial moisture results and relevant reports were obtained from forensic investigations by 'R. I .Brown', 'USL Group' and 'JM Fieldwork'. (Appendix 3).

2.4.3 Review of causes of ground movement.

The Australian practise for constructing concrete slabs is to create a level pad, and in doing so, the soil profile is often levelled by excavation or filling. The fill is generally sourced from the same allotment, solid building waste or excavated road clay which, in this area, is highly expansive. Before or after construction of houses, trees are often removed or planted and the natural drainage also sometimes altered; gardens are developed and varying watering regimes are adopted.

Geotechnical practitioners rarely consider these pre or post-construction conditions and therefore may underestimate the footing movements which affect the performance of a house during its life. This responsibility is passed-on to the property owner who is often unaware the importance of keeping the moisture stable in the house perimeter. Site Characterisation values y_s, (locally referred-to as Site Classification), are recorded out well-prior to construction and does not always meet the requirements of AS2870.

This Standard provides simple footing solutions for (y_s) which has normal soil moisture conditions. Abnormal moisture conditions, which can be caused by trees, poor drainage, leaky pipes and excessive or irregular garden watering, droughts or flooding are often overlooked or not anticipated. As a result many home sites eventually experience conditions which the owners/occupiers regard as normal but are defined abnormal in AS2870. The design surface suction range of 1.2pF in the AS2870 model is shown to have been exceeded in recent times and will not be adequate in forthcoming climate events.

The overall aim of this research project is to propose new design models for the research area considering a review of the soil parameters used for the design of slabs for light residential structures. The objectives of the research are:

- Examination of the limitations of Australian characterisation system.
- Causes and avoidance of different soil moisture during pre and post- construction.
- Investigate the performance of slabs built on basaltic soils in the research area.

- Investigate the relationship of the TMI with other relevant design parameters.
- Propose new design models for a climate similar to that recently experienced

2.4.4 Response of arid soils to wetting.

Where flat land is flooded in the drier climates Wallace and Lytton (1993) state:

“The extreme wet on the surface could be as low as 2-3pF and suggest a low threshold of 2.5pF. The extreme dry limit will be just beyond the wilting point of the vegetation and it seems that, for native grasses in semi-arid climates, this limit could be about 4.5pF”.

The osmotic suction could raise the wet threshold to 3.8pF and the dry threshold to 5+pF.

Houston[1] and Houston[2] (2014) spoke about the effect of the added water on building sites, and how urbanization–driven changes in the surface and groundwater regimes cause most of the engineering problems; e.g.:

- Landscape irrigation.
- Broken water or sewer lines.
- Roof run-off.
- Poor drainage.
- Groundwater recharge.
- Damming due to cut/fill construction.
- Concentration of water due to paving.
- Rising groundwater table and increased capillary rise.

2.4.5 Effect of soil moisture at construction stage.

A common issue with foundation moisture at construction stage is site drainage. Often this process is either done correctly, or constructed too late in the building process. A typical problem also arises when the connection of the roof drainage to the storm water system is delayed. In some cases this delay is in excess 3 months.

Leaving the site poorly drained can cause the owner some severe problems because it sometimes requires the excavation of a perimeter swale and trucking the excess soil away in a very narrow access area to improve the drainage. If the ‘covering soil’ (Notations and abbreviations) against the exposed edge beam is not properly sloped away or compacted the subsequent path contractor will lay the concrete level or without sufficient slope away from the edge of the house. (Refer to figure 39)

Walsh & Mitchell (1996) recognised the effects of soil moisture conditions at construction stage and outlined their ideas on the resulting slab shape. In the centre lift or edge settlement shape, they suggested that the design mound shape $y_m = 0.7y_s$.

Where edge lift occurs after building on an initially dry site, Walsh suggested that $y_m = 0.5y_s$ and Mitchell = $0.7y_s$.

The Standard also recommends that on a site that is wet throughout the profile at the time of construction, a reduction of y_m for edge lift, not exceeding 40%, may be made. There are other factors (not discussed here) that may eliminate or reduce this concession.

2.5 AUSTRALIAN USES OF SOIL INSTABILITY INDICES.

2.5.1 Calculation of Characteristic ground movement (y_s), in Australia.

Australian site characterisation methods rely mainly on soil indices, depth of suction and surface suction change in a set of climate conditions. A classification method by geological origin and experience in Appendix D of AS2870 uses this knowledge, grouping of soils, and regular laboratory testing in the active profile depth.

In the AS2870 existing models the Instability Index (I_{pt}) is said to be equivalent to the shrink/swell or core shrinkage index but with the application of a confinement factor in the uncracked soil layers (α). This factor depends on the position of the uncracked layer below the base of the cracked zone and is also applied to any uncracked fill. (AS2870-2011) states:

"In the absence of more exact information the I_{pt} is estimated from the I_{ps} using the following correction factor".

$$\boldsymbol{I_{pt} = \alpha .\ I_{ps}} \text{.................................... } \textbf{Equation 2}$$

<u>**α** shall be taken as follows:</u>

- In the cracked zone (unrestrained) $\alpha = 1.0$.
- In the uncracked zone (restrained laterally and vertically by soil weight) $\alpha = 2 - z/5$.
- z is the depth from finished ground level in metre to the centroid of the area defined by the suction change profile and the thickness of the soil layer in the uncracked Zone.

In AS2870 the value of the 'z' factor is given as 0.5–0.75 (H_s) for different climates. In the research area and in the absence of highly compacted layers in the 'active' profile the recommended depth of the cracked zone is 0.75 H_s= 1.7 m (where clay continues to this depth).

In the Maryland clays in the Hunter Valley of New South Wales, Fityus (1996) found a variation of α =1.92–2 and that the appropriate correction factor α is likely to be a unique value for different soils. He also states:

"It appears that the I_{ss} of remoulded soil decreases very slightly with increasing initial moisture content while the natural I_{ss} of Maryland clay increases very slightly when tested at higher initial moistures"

2.5.2 Australian laboratory test methods to determine soil indices.

The most popular soil index test in Australia is the shrink/swell test credited to Thorne (1984). This test has attempted to encourage all soil laboratories to use it since it does not need suction readings by using equation 3. To achieve a reasonable result a number of estimations have to be made. However since its first use psychrometers have become more accurate, faster and easier to use and therefore, some of the estimations are not necessary, the author has chosen to use only a conditioned core shrinkage test to make the results more consistent and comparable. The following is a brief summary of the Australian shrink/swell test and chapter 7 describes the author's CCS test.

The shrink/swell test has shrink and swell components which are measured in two separate tests. The shrink component uses a method similar to the Core Shrink test and the swell component is measured with a test similar to the loaded consolidometer swell test with samples being 20mm thick and 50 mm diameter loaded with 25kPa load. The swell test is said to be completed when the variation of swell over a 3 hour period is <0.05% of the total swell recorded to that time.

This test requires the pairing of two tests: an unloaded shrinkage test and a laterally confined loaded swell test. In equation 3 the total swell is ÷ by 2 since the confinement makes the swell 2 dimensional. Fityus, Cameron and Walsh (2009) agreed that a factor of 2 was reasonable and conservative.

$$I_{ss} = \frac{\varepsilon_{sh} + \varepsilon_{sw}/2}{1.8} \quad \text{.................................... Equation 3}$$

In this equation I_{ss} may be taken as = $I_{ps.}$ This test has been widely adopted to avoid suction measurements and does so by assuming a linear relationship of the shrink/suction over a 'floating, suction range of 1.8pF. However there are some problems with the assumed factors of 2 and 1.8 pF in equation 3.

(a) Fityus (1996) suggested adding a collar to the swell mould to prevent the 'mushrooming' of the swelling soil. This 'extension' to the brass ring is a welcome addition to the test method.

(b) The factor of 1.8pF is an approximation of the suction variation in the whole test and is used to represent very wet or very dry soils within ranges such as 2.4–4.2pF or 3.7–5.5pF. However in reality the I_{ss} and y_s will differ at these range due to the curvilinear strain/suction relationship below 3pF and above 4pF. Fredlund[1] et.al. (1999).

(c) The range of 1.8pF is too large for highly expansive clays and cannot accurately represent any dry field conditions due to the curvilinear relationship at suctions >4pF but is not a problem in benign climates where the field Δu_s is within 3 to 4pF, or thereabouts.

(d) Saline soils with high osmotic suction may cause the lower part of the shrink/suction graph to curve more sharply at suctions below 3.5pF. (Refer figure 27)

In a paper on the shrink/swell test, (Fityus et al 2009) stated:

"The simplicity of the shrink swell test is achieved, in part, by a number of important assumptions. One of these relates to the magnitude of the suction range in the test to be equal to 1.8pF units for all soils. This assumption effectively bypasses the need to measure suctions. This suction range was based on the collective experience of the AS2870 committee, and is supported by the observation that most of the volume change occurs between wilting point and suction close to saturation (≈2.4–4.2pF)".

A number of practitioners have asserted that the linear relationship may be correct at 3 to 4pF but question this assumption at the higher suctions e.g. >4pF or where there is a high osmotic suction in the lower-middle of the sigmoid (S-shaped) curve. Karunarathne (2016) has reported osmotic suctions in Braybrook research allotments in the range of 80–100kPa, (2.8–3.0pF).

Smith (1984) stated:

"It is important to determine the instability index over a suction range relative to the field situation due to the likelihood of non-linear behaviour".

Lytton (1994) suggested that the need to carry out suction/strain tests can be eliminated provided certain 'Suction Sign Posts' are followed. Since then many researchers have published sign posts that cover the whole soil moisture spectrum.

Fredlund[1] et al, (2009) quoted a linear range of 3 to 4pF and in (2011) he showed that outside this range the relationship was curvilinear and, as a whole, may be better represented by a sigmoidal curve.

2.5.3 Shrink/swell test (AS1289.7.1.1 - 1992).

In this test the initial moisture is important. If the initial (field sample) moisture is high the test becomes a shrink test. If the field moisture in the same soil is very low the I_{ss} result is lower and in extreme cases the test becomes either a shrink test (equation 4) or a swell test (equation 5).

$$I_{ss} = \frac{\varepsilon_{sh}}{1.8} \qquad \text{.......................................Equation 4}$$

$$I_{ss} = \frac{\varepsilon_{sw}/2}{1.8} \qquad \text{...........................Equation 5}$$

The Australian shrink/swell test as described above and in figure 16(a), is an example of a dry sample being tested in this manner. A wet sample using the same test gives a different I_{ss} result in dry climates. There are a number of possible causes which require a more extensive investigation. Some of these causes are addressed in Chapter 7.

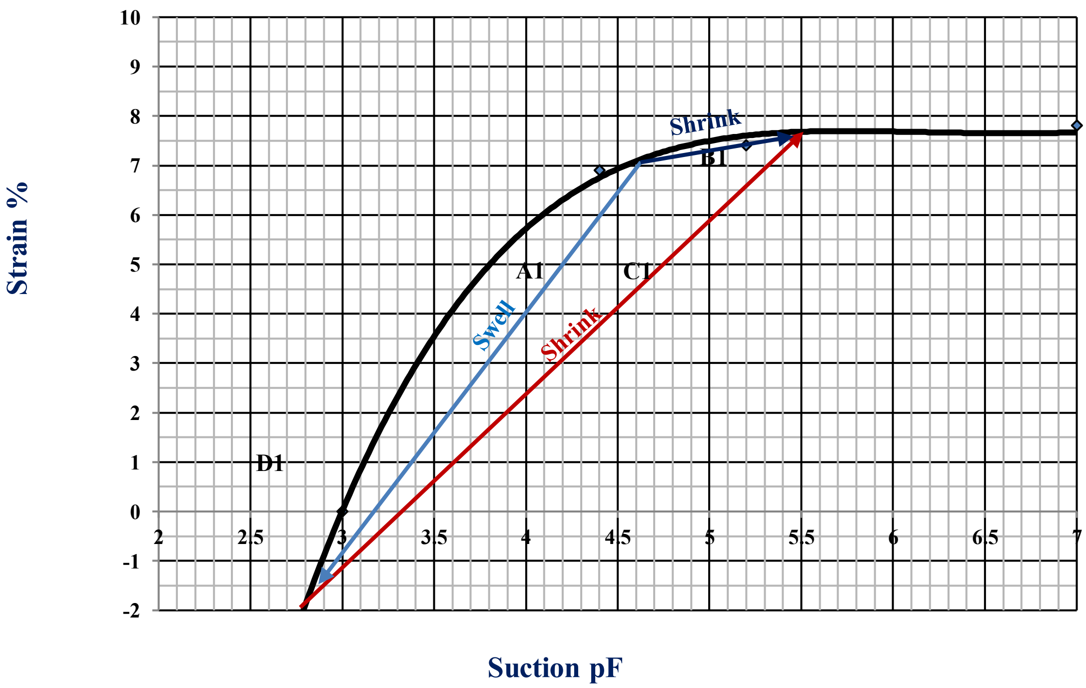

Figure 16(a): - I_{ss} from same clay samples at different moisture (Braybrook)

(The negative shrink is a projection using the program predictor)

A dry test sample would be described in the S/S test by lines A1 and B1 and with a field suction value of 4.6pF. Using equation 3 and assuming the range of suctions in Figure 16(a) the I_{ss} would be:

Line A1 & B1 (light blue & dark blue lines) from a dry sample.
Shrink 4.6-5.5pF and Swell 4.6-2.8pF.

$$I_{ss} = \frac{\varepsilon_{sh} + \varepsilon_{sw}/2}{1.8} = \frac{0.7 + (9 \div 2)}{1.8} = 2.9\%$$

Line C1 (red line) from wet sample:
Shrink 2.8-5.5pF and no further swell.

$$I_{ss} = \frac{\varepsilon_{sh} + 0}{1.8} = \frac{9.7}{1.8} = 5.4\%$$

However, if the full suction interval is used (2.8 to 5.5pF = 2.7pF) the I_{ss} = 3.6%
These results are independent of climate and the actual soil suction range and show that comparison are also difficult because this test assumes that the shrinking curve is similar to the drying curve and that both are linear for the full suction range assumed in equation 3.

2.5.4 Conditioned Core Shrinkage test.

This test was devised by the author and borrows some of the methods from other Australian Standard tests. The full description of the test can be found in Appendix 4.

$$I_{ccs} = \frac{\text{Shrink}}{\Delta u} \text{.............................Equation 6}$$

Figure 16(b) is a graphical plot of a CCS test of the same as in figure 16(a) sampled from Braybrook, Melbourne.

Line D1 (represents climate zone 3 with a Δu_s of 3.4 - 4.6pF; $I_{ccs} = \frac{\text{Shrink}}{\Delta u_s} = 3.5\%$

Line E1 (represents climate zone 3(a) with a Δu_s of 3.1 - 4.6pF; $I_{ccs} = \frac{\text{Shrink}}{\Delta u_s} = 4.1\%$

Since the samples are conditioned to a similar initial moisture the I_{ccs} is well compared and is only affected by the Δu_s and actual soil properties.

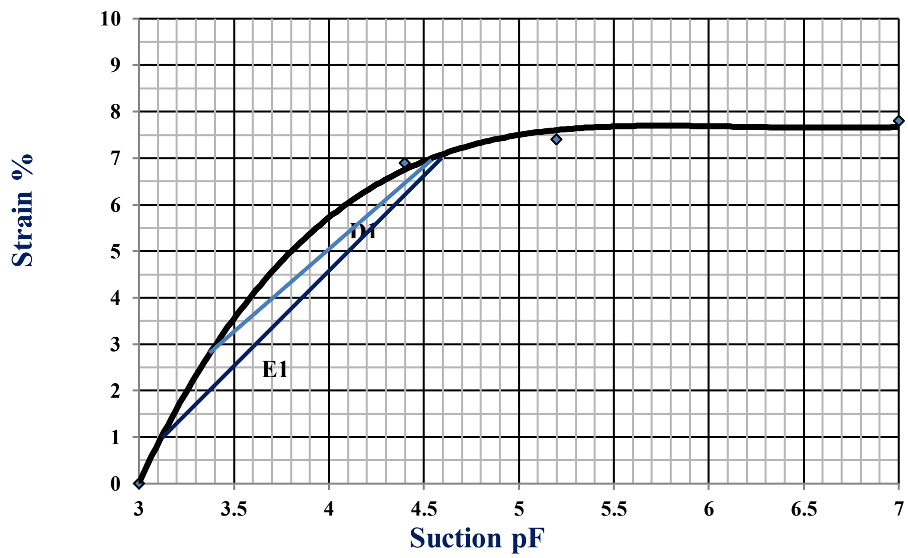

Figure 16(b): - I_{ss} from conditioned sample from climate zone 3 (D1) and 3(a) (E1).

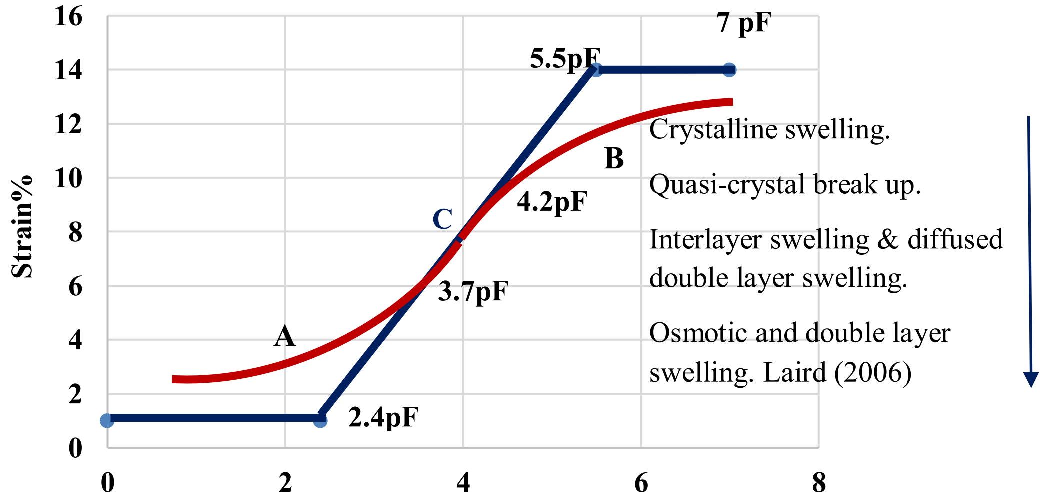

Figure 17- Graphical representation of S/S test compared to CCS test.

Figure 17 compares the linear relationship of the strain and suction used in the Australian Standard I_{ss} test with the proposed conditioned core shrink test (Line B). The author has placed the processes in their approximate position on the curve to show the complexity of the swelling processes described by Laird (2006) and which make it very difficult to accurately represent them with one straight line over the field suction span or over the of 1.8pF suction span used in equation 3 (P.43).

The swelling of Smectite clays is a complicated process initially beginning with crystalline (inter-layer) swelling followed by quasi-crystal break up, diffused double layer and osmotic swell. These processes overlap each other and occur at different swelling rates and strain.

2.5.5 Osmotic suction

This suction is usually low and constant and causes little or no swelling or shrink since it is caused by simple mineral salt accumulations. However in some cases (especially in alluvial and marine deposits) it is significant in the behaviour of certain clays. In the research area

Table 2: Filter paper osmotic readings of Braybrook soil.

Depth (m)	Gravimetric moisture (%)	Total suction (kPa)	Matric suction (kPa)	Osmotic suction (kPa)
0.3	23.01	2,346	1,630	716
	36.84	779	47	732
0.8	29.05	858	238	620
0.5-1.0	24.41	1,580	488	1,091
1.5	21.11	4,682	2,379	2,303
	23.15	3,990	1,322	2,669
2.0	23.45	3,958	1,355	2,604
2.5-3.0	22.18	2,243	1,586	657

Karunarathne (2016) reported that the clay layer in the Braybrook (part of the research area) from 1.0-2.0m is contaminated with calcrete whereas the remaining layers are not. The osmotic suction in the layer not affected by the calcrete varies from 620 – 732 kPa (average ≈ 680 kPa = 3.8pF) whereas the soil affected by calcrete had an average osmotic suction of 2,167 kPa = 3.3pF.

Other important issues in considering the measurement of soil indices are:

1. The need to estimate the surface suction interval over the 50 year life of the building.
2. Shrink/swell test (S/S) does not consider the curvilinear relationship.
3. The higher osmotic suctions are not considered in either the Conditioned Core Shrinkage test (CCS) or the (S/S). This can affect the soil indices somewhat if very wet conditions are expected in the field.

Figure 18 shows how the curve can be simplified to 2 lines (D and E) with the help of suction and shrink measurements and moisture together with measuring the soil suction and contemporaneous shrink. The curvilinear relationship can be simplified by lines **'D'** and **'E'**. Refer Appendix 5 for all results.

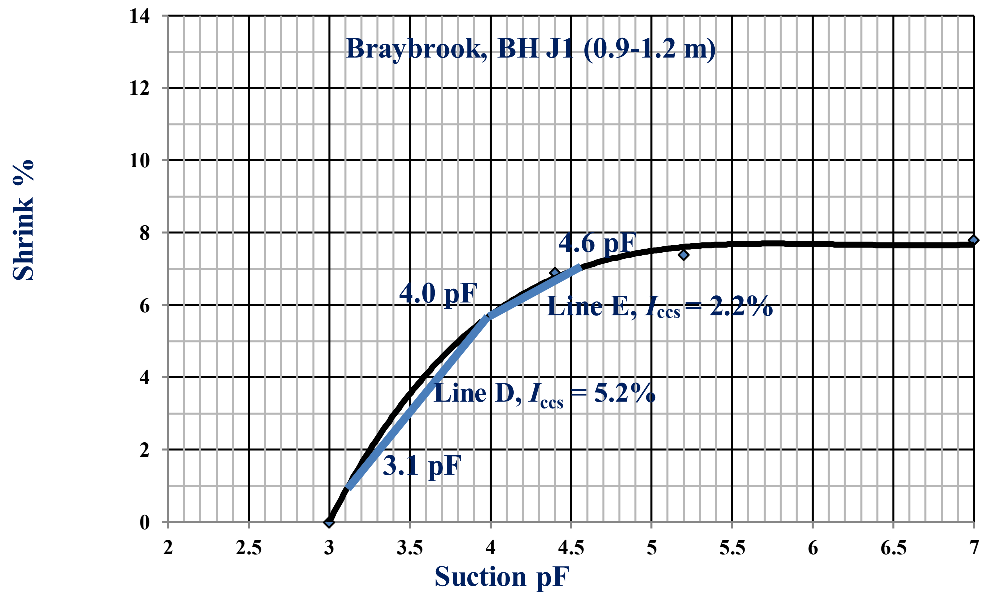

Figure 18: Simplifying the curvilinear problem for climate zone 3(a).

Following the findings in this research, the CCS can be represented by 2 different lines either side of 4pF using the actual Δu_s range for the site climate zone e.g. 3.1-4pF and 4–4.6pF with a centre point pF 4 pF for climate zone 3(a) or for a variation of surface suction in other climate zones as recommended for the new triangular models proposed in Chapter 7.

2.6 SOIL PROFILE PARAMETERS RELATED TO TMI.

2.6.1 Surface suctions.

Likos (2004) described a laboratory method for measuring the relationships such as Relative Humidity (RH) gravimetric water content (GW), and corresponding macroscopic volume change of compacted clay specimens -.

"Steady-state values are used to calculate gravimetric water content (W_G) and axial strain (ε_{sh}) by referencing the measured mass and height to initial values at a baseline oven-dried condition". This method was used in this thesis (appendix 5).

During the middle of the research period the climate changed from severe drought to abnormally wet conditions giving rise to edge and corner lifting of the on-ground slabs, particularly in those that were constructed during the most severe part of the 13 year drought.

A considerable part of the author's investigation and literature research was directed at the physical causes of clay swelling and the slab response to this movement.

The soil suction in the as-built condition is a very important parameter for design, hence, an effort should be made to establish this condition within a month or two of the finalization of the design and commencement of construction. This suction may be approximated by using SWCC test (Refer Chapter 7). The variation of suction in each soil layer can be estimated by using the surface change in suction and the new triangular models. (Figures 55 & 56).

The following are some of the relationships of TMI to the 'active' depth (H_s), Surface suction change (Δu_s) and Equilibrium suction (u_{eq}) considered in this thesis; Russam and Coleman model in figure 19 (1984) indicates that Climate zone 3 (TMI -5 to -15) has a u_{eq} of 3.5–3.9pF. For the new model in climate zone 3(a), an H_s depth of 2.3metre and u_{eq} of 4pF was used. In very dry climates u_{eq} is possibly higher.

AS2870, Table 2.4, lists several Australian areas with varying depths of design suction changes (H_s) but in each case only a general suction interval of Δu_s = 1.2pF is assigned. 'Normal' conditions, (Δu_s 3.4-4.6pF for climate zone 3) can be used to calculate y_s. However, during the research period this range was exceeded; hence Δu_s = 3.1-4.6pF is recommended and given a new Climate zone 3(a) for house design life of 50 years. The reasoning for 1.5Δu_s is based on the results from the field moistures in Appendix 3 and the shrink/suction/moisture tests in Appendix 5 and 6. (Summarised in figures 49 and 50.

The maximum dry Δu_s of 4.6pF and maximum wet of 3.1pF can be achieved anticipating that some of the man-made issues are overcome, e.g.: availability of garden water and that builders and owners/occupiers are better informed about the importance of following AS2870. A design Δu_s = 1.5pF may be appropriate for the drier climate zones however Δu_s = ≤1.2pF may still be adequate for the wetter climate zones with good drainage and good garden maintenance.

The soil moisture classification system first proposed by Thornthwaite (1931) became known as the Thornthwaite Moisture Index (TMI). The system categorises TMI on the basis of rainfall and evapotranspiration and has been used in soil/water studies in many parts of the world. The first Australian attempt at connecting climate systems to soil behaviour was made by Gentilli (1948), Aitchison and Richards (1965) followed with a TMI map of Australia. The AS2870 committee adopted the Victorian part of this map in AS2870-1996. More recently, examination of soil suction and moisture trends in Australia have been carried out by many other researchers, such as Smith (1993), Fityus, Walsh and Kleeman, (1998), Fox (2002), McManus, Lopes, and Osman (2004), Chan and Mostyn (2004), Fityus and Buzzi, (2008), Jewell and Mitchell (2009), Lopes (2010), Philip and Taylor (2013), Jie and Xi (2015), (Buxton, Osman and Lopes, (2016), Karunarathne, (2016).

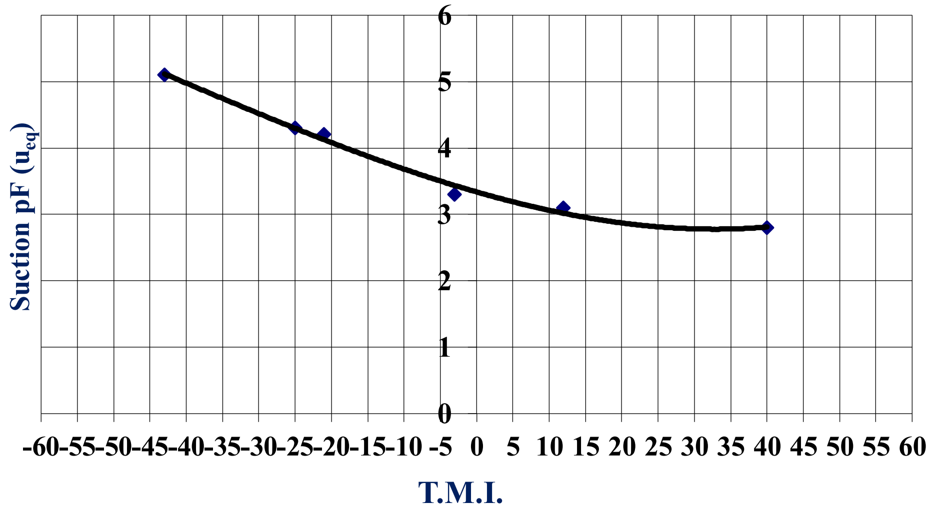

Figure 19 - TMI and Equilibrium suction. (Russam & Coleman 1984)

Table 3: – Relationship of climate zone to H_s, Δu_s and u_{eq}. (After Mitchell, 2008)

Climate Zone	H_s	Δu_s pF (wet to dry)	u_{eq} (pF)
1. Alpine/Wet coastal	1.5m	3.7 to 4.9	4.1
2. Wet temperate	1.8m	3.6 to 4.8	4.1
3. Temperate	2.3m – 3.0m	3.6 to 4.8	4.1
4. Dry Temperate	3.0m	3.5 to 4.7	4.2
5. Semi-arid	4.0m	3.55 to 4.75	4.5

Table 4: - Equilibrium suction (u_{eq}) at different climates.

Climate zone	Mitchell u_{eq} (pF)	Russam and Coleman u_{eq} (pF)	u_{eq} interpolated from research data (pF).
1	3.9	2.9	3.7
2	3.9	3.3	3.9
3	4.0	3.7	4.0
3(a)	4.0	---	4.0
4	4.1	4.1	4.2
4(a)	4.1	---	4.2

Table 5: - Relationship of TMI to H_s depth (AS2870-2011).

TMI	*H*s depth in metres)	Climate zone	
>10	1.5	1	Alpine/Wet Coastal
≥-5 to 10	1.8	2	Wet temperate
≥-15 to -5	2.3	3	Temperate
≥-25 to -15	3.0	4	Dry temperate
≥-40 to -25	4.0	5	Semi-arid
≤-40	>4.0	6	Arid

This approach allows for gradation of TMI values rather than stepped linear isopleths. Figure 16 suggests that Climate zone 3(a) - research area- has an H_s varying from 2.3 to 2.7pF. In the proposed new model the author has chosen 2.3pF.

Table 6: Six climate zones (Fityus et al 1998)

Zone No	Zone name	TMI Range	H_s depth
1	Alpine/wet coastal	>10	1.5 – 1.8 m
2	Wet Temperate	10 to -5	1.8 – 2.3 m
3	Temperate	-5 to -15	2.3 to 2.7 m
4	Dry Temperate	-15 to -25	2.7 to 3 m
5	Semi-arid	-25 to -40	3 to 3.7 m
6	Arid	Drier than -40	>3.7 m

Fityus et al, (1998) argued that the gradual TMI changes in each zone would work better than the stepped type. The author has graphically converted this table to show the gradation in various climate zones as in figure 20. This approach allows for gradation of TMI values rather than stepped linear isopleths. Figure 20 suggests that Climate zone 3(a) - research area- has an H_s varying from 2.3 to 2.7pF.

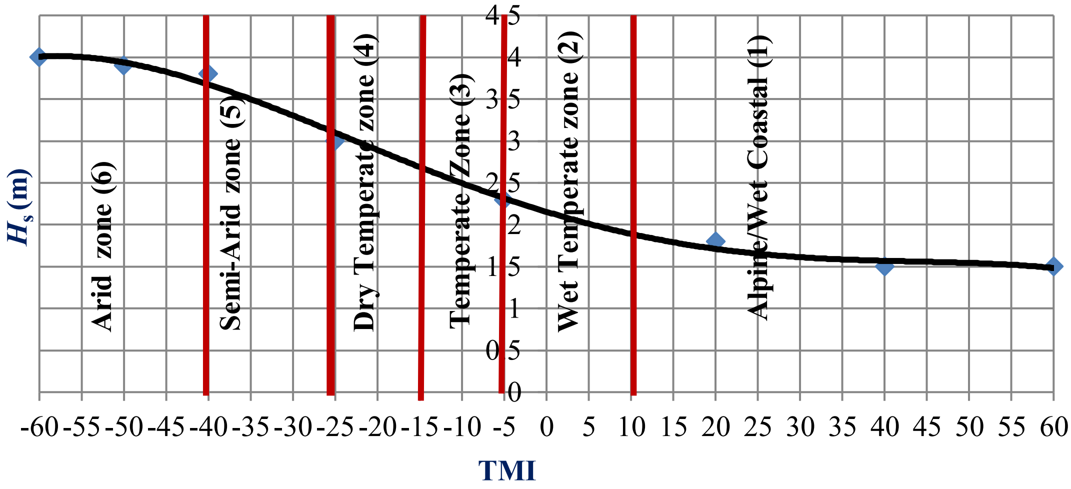

Figure 20: - Six climate zones (after Fityus et al 1998)

Hargreaves and Osman, (2014), developed a method for Queensland which uses the TMI of nearby weather station readings. This method also changes the emphasis from stepped isopleths lines to spot TMI values and has the advantage of allowing for engineering judgement particularly where there is local knowledge or significant changes in the nearby topography, e.g. on the slopes of a range of hills or near deep escarpments It also allows for more regular revisions of TMI values in new towns or suburban developments and improves the designs for a changing climate.

McManus, Lopes and Osman (2004) introduced the idea that sites prone to flooding in the drier climates would have a higher surface suction variation than other sites in similar climate zone but not flood-prone, e.g. Δu_s = 1.5pF during floods. In this thesis the term '**inundation**' is used to be inclusive of all flooding conditions, man-made or natural. Extra climate zones for inundation-prone areas could also be added to the drier climate zones.

2.6.2 Soil diffusion TMI.

Soil diffusion has become an important parameter for estimating ground movement, particularly in dry climates and cracking soils. Equations for this calculation have been put forward by a number of researchers as early as Richards (1967). Mitchell (1979) published a variation of Richard's equation in 1979 surface suction Δu_s which was and later used to estimate the H_s, Δu_s and α values for the y_s calculation model in AS2870.

Mitchell (2008) arrived at the values in table 6 by analysing his diffusion equation. He describes the dry climatic conditions and the problems of building in Australian arid areas as follows:

"The arid regions of Australia are characterized by summers with very high day-time temperatures and hot nights, low relative humidity day and night, and winters comprising warm to hot days and cool to cold nights. Rainfall is very irregular, but usually occurs as storms which cause the ephemeral creek and river systems to flow, often leading to regional flooding. The parameters required for the design of footings on expansive clays for arid regions are derived theoretically from established relationships experienced in more temperate climates".

In the above study (2008) Mitchell also quoted two critical parameters for these conditions using a diffusion equation; surface suction $\Delta u_s = 1.8$pF and the depth of design suction change H_s = 2.5 metre. AS2870-2011 recommends Δu_s = 1.2pF and H_s = 4 metre for the same conditions.

Table 7: – Diffusion coefficient in climates and TMI. (Mitchell 2008)

Climate Zones	TMI	Diffusion coefficient cm^2/m
1. Alpine/Wet coastal	>10	≤ 0.0005
2. Wet Temperate	≥ -5 to 10	0.0005 to 0.0008
3. Temperate	≥ -15 to ≤ -5	0.0008 to 0.0013
4. Dry temperate	≥ -25 to ≤ -15	0.0013 to 0.0017
5. Semi-arid	≥ -40 to ≤ -25	0.0017 to 0.0029
6. Arid	≤ -40	> 0.0029

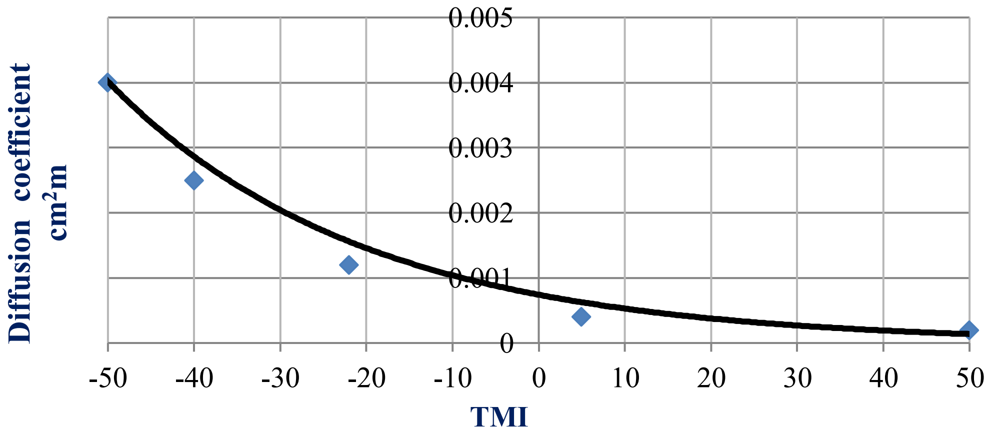

Figure 21: Soil diffusion and TMI (after Mitchell 2008)

Mitchell (2008) suggested that the Diffusion Coefficient (α) increases with aridity. This would be expected as the degree of cracking and fissures in the soil profile increases with increasing aridity, thus increasing the permeability of the soil profile, hence the diffusion coefficient would also increase.

He also stated that in drier climates such as in Albury-Wodonga (climate zone 4) the H_s may be 3 metre (as proposed in AS2870) but that the value of Δu_s may significantly exceed 1.2pF and similarly in Adelaide the Δu_s is unlikely to be 1.2pF but closer to 2pF, as he measured in a long-term investigation in O'Halloran Hill (1983).

Interpolating tables 3, 4, 5 and figure 19, quoting Mitchell, Russam, Coleman and AS2870 the author proposes the following parameters for the new site characterisation models:
For Climate zone 1, 2, 3 and 3(a) the u_{eq} chosen is 4pF. For climate zones 4 and 4(a), it is 4.1pF. The original TMI, and H_s table published in AS2870 – 1996 was also considered.

Recently BoM published Australian Water Resources Assessment maps of Landscape Water Balance Model (AWRA-L) which are quoted on a daily basis or on a monthly or annual average for surface, below surface and deep conditions. This service could be used as a design input of the as-constructed moisture condition in the building site.

2.6.3 Characteristic surface movement.

The conventional methods of predicting expansive soil movement in Australia as per AS2870 is the Shrink/swell test (Thorne 1984) which assumes a linear relationship between the soil vertical strain and the change in log soil suction (u) and the Instability Index I_{pt}, which is used as a soil constant.

AS2870-2011 states that (u) is taken as the difference between the characteristic dry suction and the characteristic wet suction over the depth of design suction change H_s. The characteristic surface movement (y_s) is given by equation 8, P. 82.

The design suction change is assumed to be a linear triangular distribution with surface suction change (Δu_s) decreasing linearly with depth to H_s until the soil almost constant (u_{eq}). These are important variables that vary according to locality and climate.

2.6.4 Soil-water characteristic curves (SWCC).

SWCC have been used for many decades and popularised more recently by Fredlund[1]. These tests are simple and very useful for forensic investigations.

Sillers et al (2001) has also worked on SWCC and says:

“Some of the commonly used SWCC equations take the form of a continuous function that is asymptotic at the extremities. It is the zones between the air-entry value and residual suction: where the curve has sufficient slope for the calculation of soil suction”

Fredlund[1], Cheng, and Zhao, (2011) wrote about SWCC:

“There are two distinct changes in slope along the Suction Water Characteristic Curve (SWCC). The changes in slope define two points that are pivotal to describing the SWCC. The first point is termed the ‘air-entry value’ of soil; (where the largest voids start to de-saturate as suction is increased). The second point is termed ‘residual condition’ and it defines the point where the removal of water from the soil becomes significantly more difficult (i.e. requires significantly more energy for water removal)”

“The changes in slope subdivide the SWCC into three distinct zones, namely the ‘boundary effect zone’ in the lower suction range, the ‘transition zone’ between the air-entry value and the residual value and the ‘residual zone’ at high soil suction reaching up to 10^6 kPa (7pF). Likewise, there are similar distinct changes in slope along the wetting SWCC”. (Figure 22)

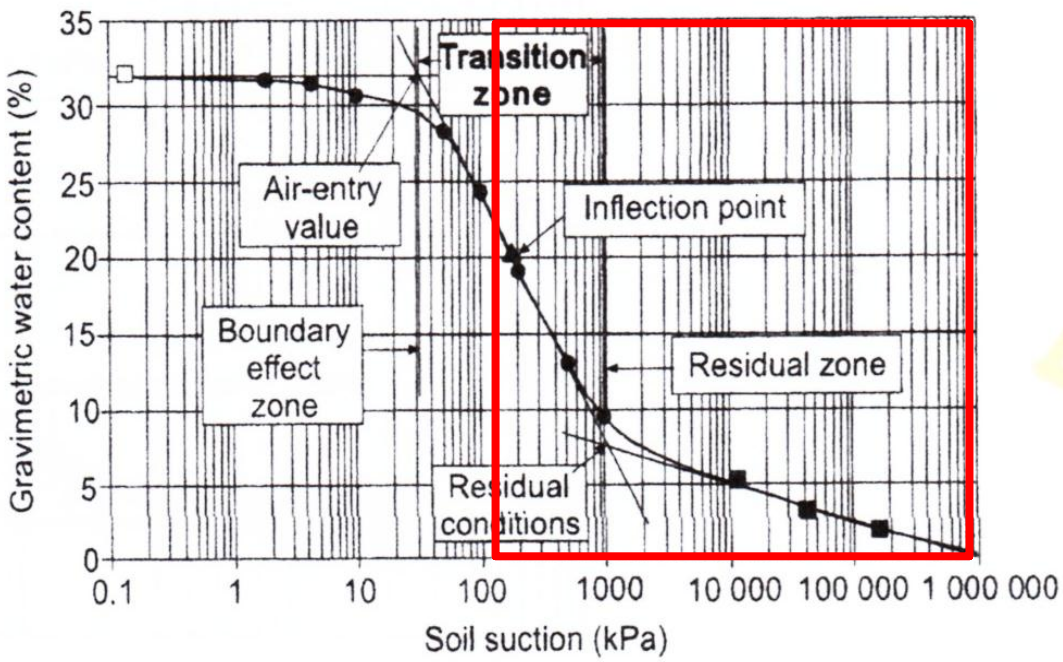

Figure 22 - Typical SWCC, Fredlund[1] et al (2011)

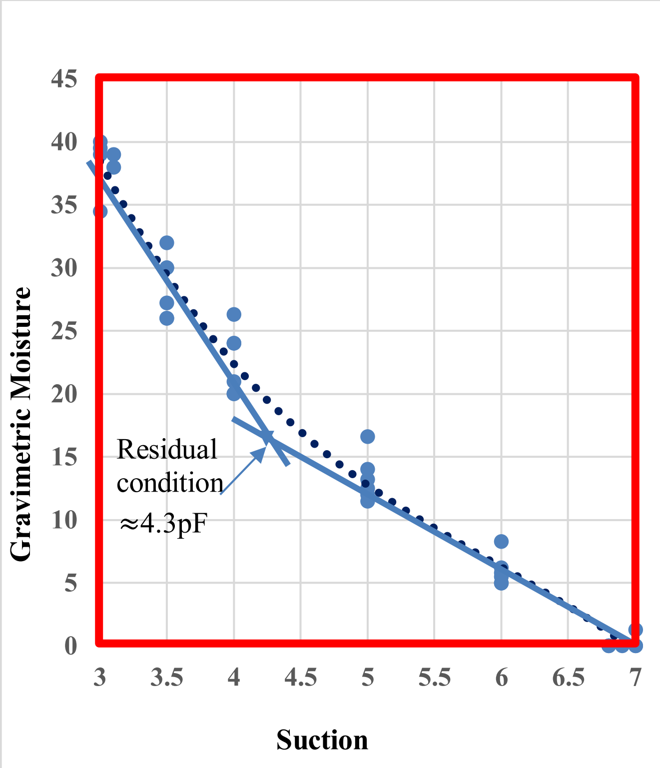

Figure 23: - Grouped SWCC from research area (Appendix 6)

<u>Figure 23 has the X and Y axes in the same order as Fredlund et al. Elsewhere the X and Y axes have been drawn in the reverse order by the author.</u>

McKeen, and Nielsen (1977), suggested that:

"The bilinear nature of the SWCC reflects the physicochemical nature of the water interaction between micelles and within the micelles. The bifurcation point on the curves may be considered analogous to the air-entry pressure for granular soils. However, there is not an abrupt change to an unsaturated state at that point"..."This bifurcation point represents a transition between micro pore and macro pore spaces. The macro pore spaces would represent the spaces between aggregates of particles and the micro pore spaces would represent the spaces within the aggregates".

A number of other researchers have also observed similar behaviour for expansive soils Marinho (1994); Chao (1995); Miller (1996); Chao et al. (1998); Fredlund[1] Chang and Pham (2006); Miao, Jing and Houston (2006); Puppala, et al (2006); Chao et al. (2008), Pham and Fredlund[1] (2008).

2.6.5 Conditioned shrink–suction characteristic curves (CSS).

Different models have been proposed for describing the soil shrinkage characteristic curves. All models are sigmoid (S-shaped) curves. Fredlund[1] et al (1999) quoted that the relationship of suction and shrink is made of curves at suctions above 4pF and below 3pF and linear in-between. However in the field suction range 2 lines can be used e.g.: 3–4pF and another line for the remainder range. Figure 22 shows 2 lines representing the Δu_s surface suction for climate zone 3(a) i.e. 3.1-4pF and 4-4.6pF

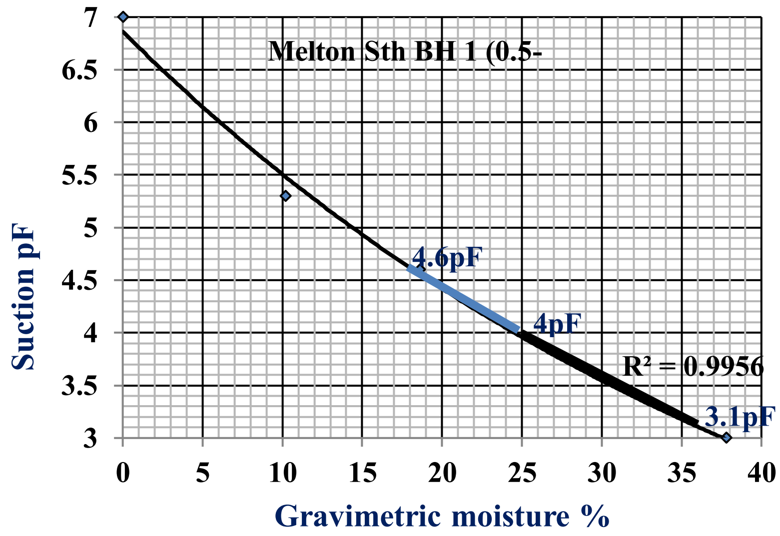

Figure 24: - Typical SWCC from CCS – Melton South. (2015)

The SWCC can be determined from the CCS test merely by weighing the (A) shrink sample (figure 43) at each suction test. These graphs were found very valuable in determining possible past and future ground movements by comparing them with field moistures taken at construction and later stages.

Example:

In the test sample from Melton South in figure 24 a field moisture of 36% suggests a suction of 3.1pF, hence, it is highly likely that the foundation soil will dry in the future. The reverse can also be relied upon e.g.: a sample reading a suction of say 4.5 pF (≈19%) is likely to wet-up and cause edge lift.

2.6.6 Hysteresis in compacted clay testing.

Tripathy, Subba, Rao and Fredlund[1], (2002) addressed the behaviour of compacted expansive soils under swell-shrink cycles. Laboratory cyclic swell-shrink tests were conducted on compacted specimens of two expansive soils at surcharge pressures of 6.25, 50 and 100kPa.

"Depending on the situation various deformations such as vertical deformation and/or lateral deformation are of great interest to the designing engineer, Volume-change measurements and vertical-deformation measurements are common problems in geotechnical engineering practice because of the absence of a specific test procedure for lateral swelling measurements".

These authors reported that the swell-shrink path was reversible once the soil reached an equilibrium stage where the vertical deformation during swelling and shrinkage were the same. They stated that this usually occurred after about four swell-shrink cycles.

This suggests that compacted fill may be considered similar to natural ground after 4 drying and wetting seasons. (AS2870 accepts 5 years)

These authors also discuss that the swelling and shrinkage path of each specimen subjected to full swelling and full shrinkage cycles showed an S-shaped curve with two curvilinear portions and a linear portion. The linear portion is in the central portion of the S-shaped curve. They suggest that the swell-shrink paths can be established with a limited number of tests in the laboratory.

The author has reasoned that the hysteresis behaviour occurs in very recently compacted soils and not in undisturbed natural samples. The samples used in Appendix 5 were in-situ weathered and only tested for shrinkage, hence hysteresis was not considered problem. The soil types investigated were 'natural' and ideal for sampling with 'Shelby' tubes due to their cohesion and absence of coarse material.

A review of the literature indicated that there has been considerable interest in understanding the cyclic swell-shrink potential of expansive soils. This has been accomplished by measuring the vertical deformation of soils undergoing cycles of swelling and shrinkage. The change in volume of the soil and the changes in water content from the shrinkage to the saturation state and from the saturation state to the shrinkage state have been studied by many researchers.

In many laboratory research methods, slurry soil specimens are used to determine the shrinkage limit of the soil. In most of these methods, the specimens are dried for one cycle with zero external stress applied.

American Society for Testing and Materials comments on the test method, ASTM 1998c D427.

"During structural shrinkage a few large, stable pores are emptied and the decrease in volume of the soil is less than the volume of water lost.

During the normal shrinkage phase, volume decrease is equal to the volume of water lost (i.e. the slope of the total specimen volume versus water content line is 45°). On further drying, the slope of shrinkage curve changes and air enters the voids at the shrinkage limit or at the start of residual shrinkage. As the particles come in contact, the decrease in specimen volume is less than the volume of water lost. Lastly when all the particles come close together, no further shrinkage occurs while water is still being lost”.

Zhan and Chen (2007) commented that:

“Hydraulic hysteresis (sometimes referred-as ‘ink-bottle effect’) of the natural specimen was relatively insignificant as compared with compacted specimens”

“This effect considers the amount of void space in a granular soil comprised of different grain sizes during wetting and drying for describing the hysteresis phenomenon. In the case of clayey soils, however, particle re-arrangement during shrinkage and swelling and changes in water content complicate the understanding of the hysteresis phenomenon. It is not fully understood whether the water content alone or the water content and void ratio together are responsible for hysteresis along the wetting-drying path of a clayey soil”.

Mitchell (1976), stated that although swelling and shrinking of expansive clays are inter-related, it is uncertain whether highly swelling clays also show equally high shrinkage.

Nelson J.D., Chao, Overton and Nelson E.J (2001) state:

“The expansive nature of soil having an abundance of multivalent cations is much less than soil having only monovalent cations. For example, if the sodium cations in the micelle are replaced by divalent calcium cations (Ca^{2+}), there would need to be only half as many cations present to balance the negative charges on the clay particles and the size of the micelle would shrink”

”Similarly if the absorbed cations were divalent, there would be half as many present, and the expansion potential would be less. In addition, the bonding strength of the divalent cations can be greater than for the monovalent cations”

”The soil water characteristic curve (SWCC) defines the relationship between water content and soil suction. Although the SWCC will be influenced by applied stress, it is usually defined for conditions where the normal stress is small. The water content is generally quantified in terms of gravimetric water content, volumetric water content, or degree of saturation. These parameters can be used to define the SWCC provided the reference volume of the soil remains consistent".

Benson and Meer (2009) quoted:

"Clays having an abundance of monovalent cations had a much higher soil index than those with an abundance of divalent cations. As may be expected, the matric and osmotic suction will vary with the water content. However, within the range of water content changes that occur for most practical applications in geotechnical engineering, it has been shown that the osmotic suction changes little, if at all".

2.6.7 Soil suctions and common test methods.

Evans, McManus and Mann (1998) described soil suction very clearly in this way:
"Soils such as clays, silts or sand, which differ in their physical properties and have equilibrated in a common environment, will differ in moisture content, but not in their water potential, affinity or soil suction. Absorbed water is held by forces of absorption on the surface of the soil particles. Bipolar water molecules are attracted to plate-like surfaces of clay particles because of negative electromagnetic charges concentrated in the particles. The maximum quantity of water held by surface absorption depends primarily on the surface area of the particles, which is greater in fine-grained soils such as clays"

"Hence it can be said that soil suction is made of many forces which are responsible for soil swelling, shrinking and soil water retention".

Sogy et al. (1980) have written on the shrink-swell cycles in compacted specimens

."Since height increases after shrink-swell cycles, the swell/shrink behaviour of an expansive soil is not completely reversible". This applies only to compacted samples.

In figure 25, Snethen (1980), shows that the wetting curve does not follow the drying curve in compacted specimen. He also described 2 types of suctions:

"The total soil suction consists of two components, matrix (matric) suction, and osmotic (solute suction). Osmotic suction arises from the presence of soluble salts in the soil water. The polar nature of water causes the water molecules to be attracted to ions in the soil solution".

Krahn and Fredlund (1972) plotted 4 suction lines, Matric, Osmotic, Osmotic + Matric and Total suction (by psychrometer testing), figure 27. Laird (2006) recognized 6 processes in soil swelling which may overlap these suctions, (Refer Ch. 2, 2.22)

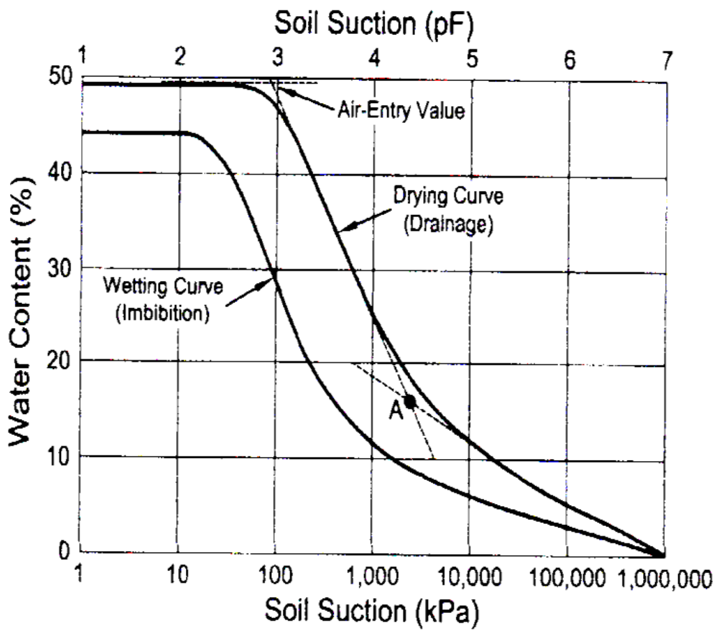

Figure 25 - Shrink and swell curves from compacted specimens.

From the shape of the shrink/suction graphs in this thesis it is estimated that osmotic suction in the tested clays could be as high as 3.5pF. Karunarathne (2016) has quoted up to 800 kPa (3.9pF) from a site in Braybrook using a Tensiometer.

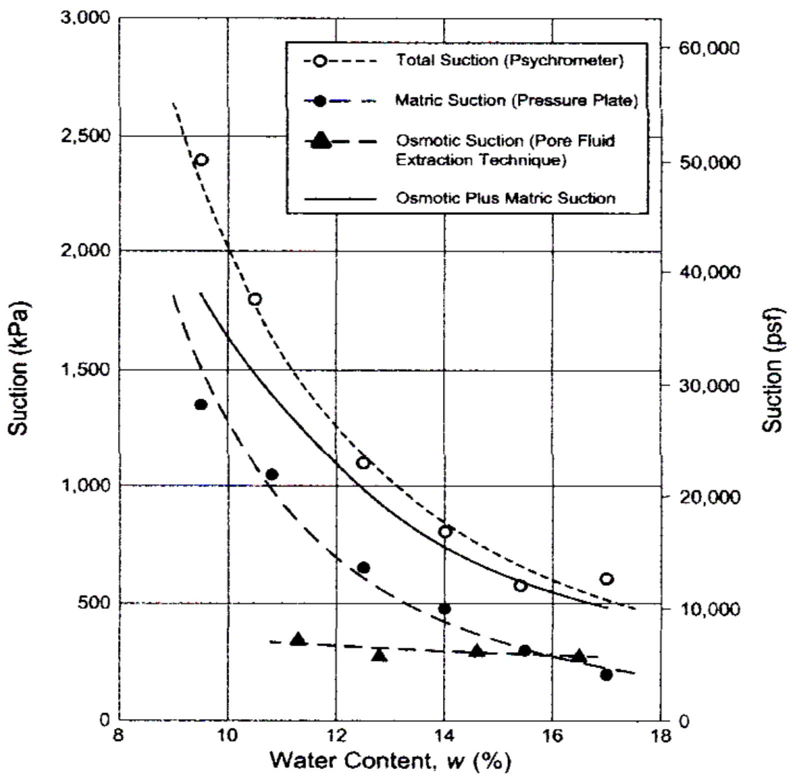

Figure 26: - Total, matric and osmotic suctions, Krahn and Fredlund[1] (1972)

2.6.8 Cracked and un-cracked soil zones.

During dry seasons evapotranspiration causes loss of water in the shallow soil layers and an increase of soil suction and soil cracking. In wind-blown plains these cracks are often partly filled with sand, silt and clay. During rain periods water infiltrates into these cracks and initially causes proportionally greater lateral swelling. Once the cracks have sealed the swelling becomes more vertical in response to the lateral confinement and low vertical confinement.

This action is repeated in ensuing droughts and wet periods. In time the soil profile develops thin flute-shaped cracks which fill with Aeolian deposits with a more granular composition than the original clay profile. (Figure 27).

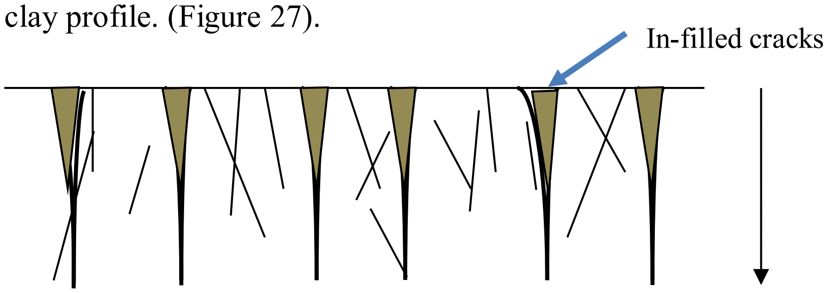

Figure 27: Development of the cracked zone.

Fredlund[1], Houston[2], NG, and Fredlund[2] (2010) on moisture in cracked soils stated:

"Clay soils start to crack from the ground surface as matric suction increases. The low confining pressures near the ground surface allows clay soils to commence cracking at relatively low matric suctions. The cracks generally become closed with depth as the confining pressure increases. It is difficult to estimate the hydraulic conductivity and the water storage properties of the cracked clay i.e. fissured and fractured clays".

In discussing the rate of water penetration these authors also state that the behaviour of physical processes, hydraulic conductivity and water storage associated with a cracked soil are notably different from those of an intact soil. Fractures (cracks) in a soil mass dramatically change the mechanical and hydrological behaviour of a porous medium. The fractures provide a preferential flow pathway, reduce shear strength and increase the saturated hydraulic conductivity of the soil.

To allow for the effect of soil cracks during swelling, AS2870 advises practitioners to apply the following factor, $\alpha = 2.0 - {}^{z}/_{5}$ to modify the Instability Index (I_{ps}). The z depth is measured in metre from the finished ground level to the centroid of the area defined by the suction change profile and the thickness of the soil layer under consideration in the uncracked zone.

In the absence of more exact information, this Standard also advises that the depth of the cracked zone shall be taken as:

1. 0.5 H_s to H_s where H_s is as given in the (AS2870, Table 2.4)
2. 0.75 H_s in Adelaide and Melbourne,
3. 0.5 H_s in other areas.

The factor α in the uncracked zone converts the I_{ps} to I_{pt}. In the cracked zone $I_{ps} = I_{pt}$.

In AS2870 the lateral restraint factor α in 'Controlled' fill is considered uncracked and therefore α is Zero (if laid less than 5 years prior to building). Where a site has been cut less than 2 years prior to building construction, the depth of the cracked zone is reduced by the depth of the cut.

Most local geotechnical practitioners are aware that the compaction of fresh fill can close the original surface soil cracks and therefore reduces the depth of the cracked zone in the underlying natural soil but only a few consider this in their y_s calculations.

2.6.9 Response of arid soils to wetting.

Houston[1] and Houston[2] (2008), in a lecture series in Australia spoke of the engineering problems caused by urbanization–driven ground water changes, such as:

- Landscape irrigation.
- Broken water or sewer lines.
- Roof runoff.
- Poor drainage.
- Groundwater recharge.
- Damming due to cut/fill construction.
- Concentration of water due to paving.
- Rising groundwater table and increased capillary rise.

Many of these ground water changes have played a significant role in the house damage experienced in the research area in the past 2 decades. (Appendix 1 and 2).

Most arid areas in Australia have very little elevation and are 'inundation prone'. The effect of this causes slab edge and corner lift.

Interpolating tables 3, 4, 5 and figure 19, quoting Mitchell, Russam, Coleman and AS2870 the author proposes the following parameters for the new site characterisation models:

For Climate zone 1, 2, 3 and 3(a) in this thesis the u_{eq} chosen is 4pF. For climate zones 4 and 4(a), it is 4.1pF. Many researchers have published variations of the TMI, and H_s.

2.7 SWELLING OF BASALTIC CLAYS.

The basaltic clays in this research project are mainly Montmorillonites which have degraded from Ca++ type to Na+ types and have become very highly expansive with Liquid Limits in the general range of 70% - 130%.

On this topic Laird (2006) stated:
"Six separate processes control the swelling of Smectites saturated with alkali and alkaline earth cations in aqueous systems. They swell by imbibing water or polar organic solvents between their quasi-crystals and/or between the individual layers within the quasi-crystals causing:

- Crystalline swelling.
- Double-layer swelling.
- Co-volume swelling.
- The breakup of quasi-crystals.
- Cation de-mixing.
- Brownian swelling

One of these processes may dominate in a particular clay-water system, but generally a number of them operate in concert and determine the swelling rate of a sample. Sodium (Na+) preferentially concentrates in certain inter-layers, and has a large influence on the break up and formation of quasi-crystals which increases swelling".

These shrinking and swelling processes acting in concert would not have a linear relationship throughout.

Likos and Lu, (2006) report that efforts to address the damage caused by clay swelling have, historically, focused on measuring or predicting volume change and associated swelling pressure within the osmotic swelling range but very few studies have explored bulk swelling behaviour within the crystalline swelling regime.

2.8 METHODS FOR MEASURING OR ESTIMATING SUCTION.

The most commonly used methods for measuring soil suction include:

- Tensiometers,
- Psychrometers.
- Filter paper.
- Thermal conductivity sensors.
- Electrical resistance sensors.
- Pore fluid extraction technique.

The measurement of total suction is based on the principle that the energy state of air is a function of its relative humidity and the energy state of the soil water is the total suction. The most common equipment for measuring total suction in Australia is the psychrometer (recently the chilled mirror dew point type has become the most popular) and filter papers. Tensiometers or filter papers are sometimes used to measure matric suction and osmotic suction can be measured by subtracting the matric suction from the total suction. However two different calibration curves are necessary.

(a) Filter Paper method for measuring total suction - Measuring total suction is basically the same method as measuring matric suction, except that the filter paper is not into contact with the soil.

Houston[1], Houston[2] and Wagner et al, (1994) developed two different calibration curves, one for total suction and one for matric suction, using 'Fisher' quantitative coarse filter papers. For the total suction calibration curve, saturated salt solutions were used and for matric suction tensiometers pressure membranes were used. They reported:

"The total and matric suction calibration curves were not compatible. This simply implies that two different calibration curves, one for matric and one for total suction, need to be used in soil suction measurements".

Bulut, Lytton and Wray (2001) describe how a single curve is constructed by using different filter papers, a combination of different soil suction measuring devices, and different calibrating testing procedure".

(b) Chilled Mirror Psychrometer. This method uses the same principle as the thermocouple psychrometer, except that the soil sample is placed inside the psychrometer in a temperature controlled chamber which contains a small mirror. The temperature of the mirror is controlled by thermocouple circuitry and is cooled to the dewpoint at which time condensation appears on the mirror. The total suction is determined from the temperature of the mirror at this point and the vapour pressure of the air in the chamber.

(c) Empirical Methods. A number of these have been used and are mostly based on test data collected from ta particular geographic region in which they were developed. Other methods include using standard suction solutions, Gypsum blocks, Free Swell etc. Researchers have also quoted a number of suction 'sign posts' based on average laboratory results: Lytton (1992) presented a number of these at a series of lectures given at 'Vic. Roads' in 1992. The author has found the following most useful as a guide in both field and laboratory testing to estimate matric suction.

Table 8: Soil Suction 'Sign Posts from 3 to 7pF'

Suction pF (Unloaded).	Soil state.	Researchers.
≈6.5 - 7+	Oven dry	Lytton, Leeper, Uren, Mitchell et al.
≈6.0	Air dry	Lytton, Leeper, Uren.
≈5.5	Shrinkage Limit	McKeen, Mitchell et al.
≈4.2 - 4.5	Wilting Point	Lytton, Leeper, Uren et al.
≈3.2 - 3.5	Plastic Limit	Lytton.
≈3	0.4 L.L.	Driscoll.

2.9 CHAPTER 2 CONCLUSIONS

The research quoted in this chapter is a small window into the work carried out by many world known scientists in the past 60 years into the problems and solutions of clay behaviour. It is evident that much is yet to be learned about the soil medium and how complex is its nature.

The engineering profession is always looking for elusive mathematical answers about materials that are considered so simple yet so problematic. This is particularly so in the residential building industry which is so fundamental for our living environment. The total costs are so high yet the techniques and skills so underrated.

The following chapter (Ch. 3) explains and discusses the local practise in the characterisation of building sites for light dwellings and some of the more important design and construction procedures mentioned in AS2870.

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CHAPTER 3

SITE TMI & SOIL PARAMETERS

3.1 SOIL PARAMETERS FOR SITE CHARACTERISATION.

The most important factor for site characterization is the size and shape of the model used. The author has used a variation of the AS2870 triangular model. (Chapter 6). Climate and the soil profile of the "active" zone are the main controlling factors in this model which include:

1. "Active" depth (H_s).
2. Surface suction range (Δu_s).
3. Each soil layer depth being considered.
4. Average layer suction.
5. Depth of cracked zone.

Parameters 1 and 2 are related to climate and in particular to the Thornthwaite Moisture Index (TMI) of the site.

3.2 THORNTHWAITE MOISTURE INDEX.

While weather is the sum total of the atmospheric variables for a relatively short period of time, the climate of an area is determined over much longer periods and represents the general weather characteristics of an area or locality. One of the older and best known systems was the "Moisture Index Thermal Zones" first published in 1900 by Köppen. Mather's modification of this system was first published in 1978.

Thornthwaite pioneered the "water balance model" to assess water needs for irrigation in 1931 and in 1948 produced a "moisture index" map for the U.S.A. Aitchison and Richards calculated and mapped this index for Australia in 1965 using 1940-1960 data from BoM.

In writing about the 'water balance' model Mehta et al (2006) stated:

"Water balance is a budgeting exercise that assesses the proportion of rainfall. The major input is precipitation and major output is evapotranspiration".

In 1996 AS2870 adopted the TMI to assess the depth of soil moisture change for the Site Characterisation model (Chapter 3). This thesis has used up-dated TMI's to assess the engineering effects from climatic conditions in the past 70 years in the research area.

Buxton et al (2016) state how the “water balance” is used. They quote McKeen (1993) that there are 3 components for calculating TMI:

(i) Determining potential evapotranspiration based on Morton’s calculation method.

(ii) Computation of a moisture balance to determine allocations of water storage deficit and run-off.

(iii) Computation of annual summations that are used to determine the index value.

Buxton et al calculated the TMI values from the BoM climate data and the original Thornthwaite formula (equation 7). The evapotranspiration values used were supplied by “SILO” and were calculated from BoM weather station data.

TMI = (100D-60d)/Total Ep..........................Equation 7

In their book on Climatology, Rohli and Vega (2007) state that “climate is highly geographical” and emphasized the use of the TMI.

Peterson, Sack and Gabler produced the map (Figure 28) to show the TMI over a 30 year period in the USA. The research area for this thesis would be similar to the Dry-Subhumid climate in South Central USA. The TMI system was quickly adopted by the engineering profession in Australia and maps were produced by Gentilli (1948) and Aitchison, Richards, Peter, Emerson et al in the 1960’s and recently brought up to date by many Australian researchers.

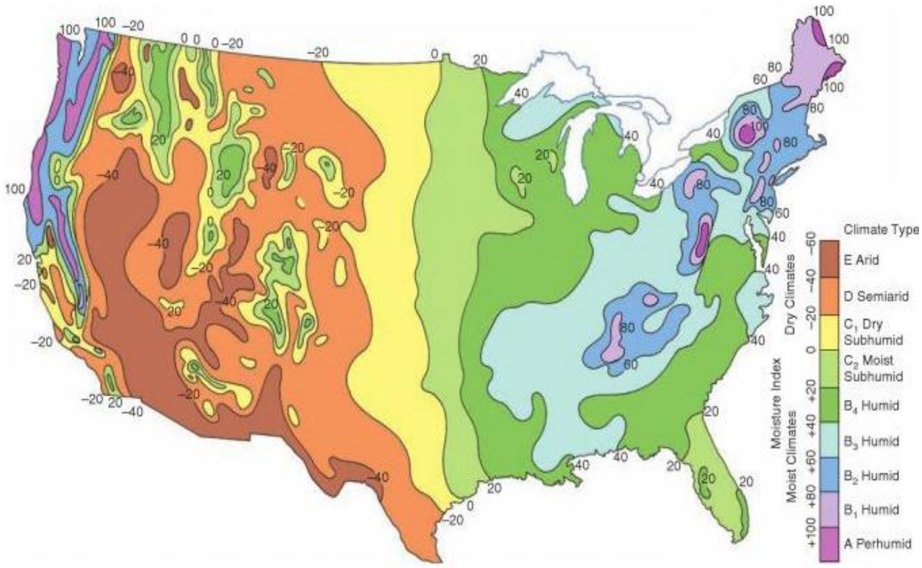


Figure: 28 - Thornthwaite climate regions in the contiguous (USA), (Peterson, Sack and Gabler)

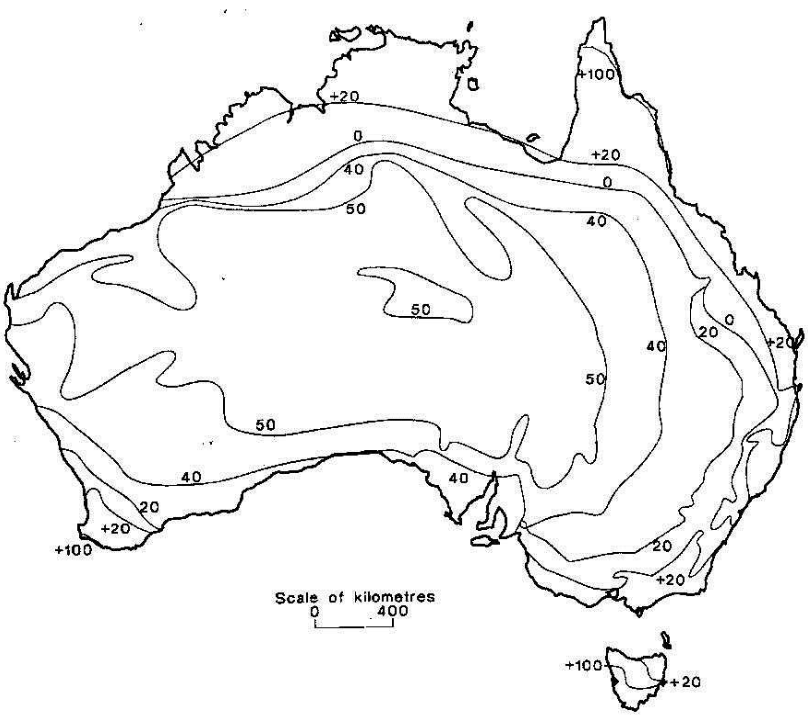


Figure: 29 – Early TMI map of Australia (Gentilli - 1948)

In this map any positive TMIs are shown with a + while the remainder are negative - .

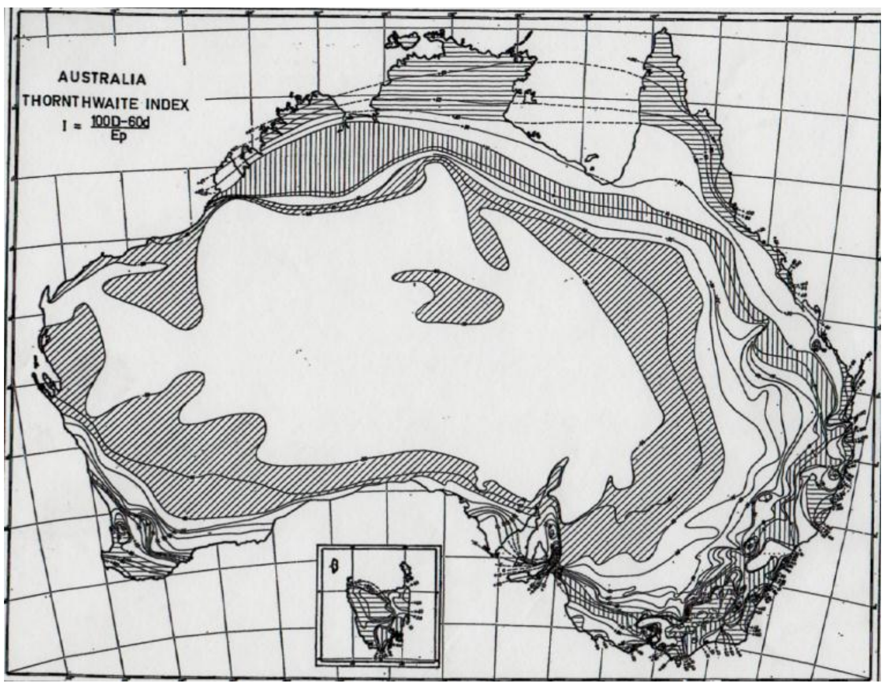


Figure: 30 – TMI map of Australia (Aitchison and Richards – 1965)

3.2.1 TMI changes in Victoria (from 1948 to 2013)

A Victorian TMI map was published for the 1996 edition of AS2870 (figurer 31) with climate types peculiar to this standard. It is part of the map published by Aitchison and Richard (1965) using the original TMI formula (equation 7) and from data recorded from 1940-1960 by (BoM). This map has been maintained for the latest issue of AS2870 (2011). The research area was considered Climate Zone 3 based on a TMI range of ≤ -5 to ≥ -15.

Figure: 31 - TMI map of Victoria (AS2870-2011)

Buxton, Osman and Lopes, (2016) re-calculated the TMI values as shown in figures 32(a), (b) & (c), from 1948-2007 using (BoM) and SILO information from 660 weather stations. Osman-Schlegel and Leao extended this research to 2013 using the results from to 1,660 weather stations and applying a computer generated topographical factor (Figure 33).

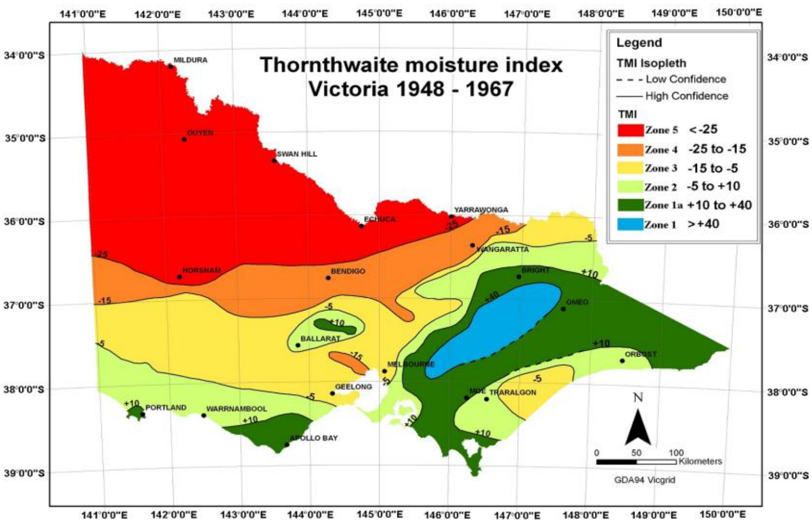


Figure 32(a)

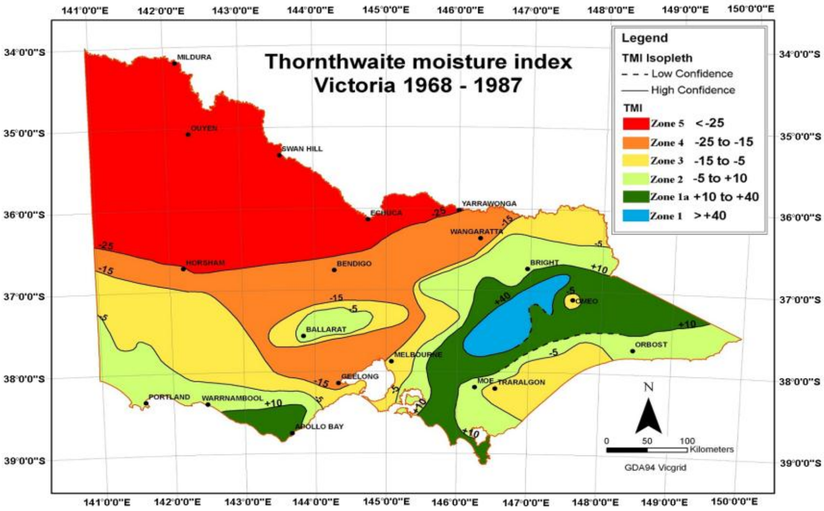
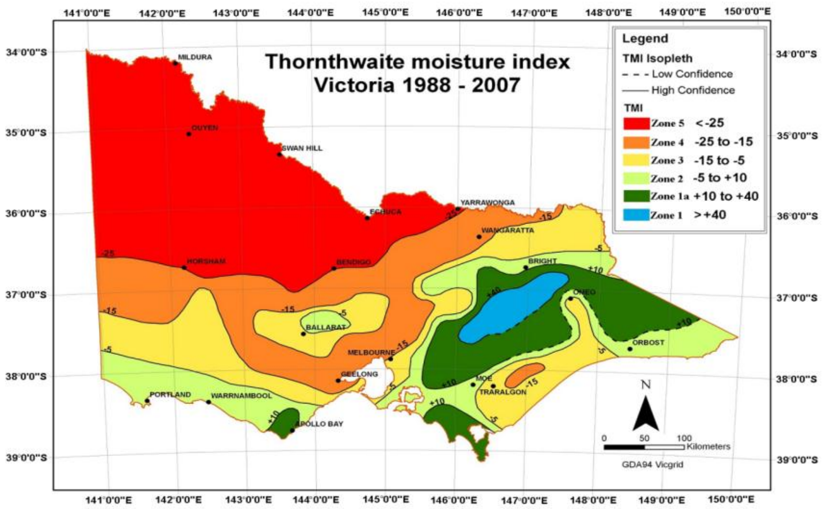


Figure 32(b)



Figures 32(a), (b) & (c): - TMI maps of Victoria (Buxton, Osman & Lopes 2016)

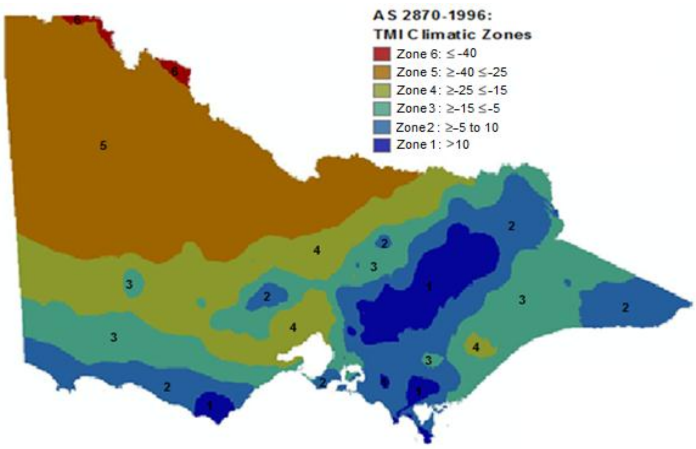


Figure 33: - TMI map of Victoria, Leao and Osman-Schlegel, (2013)

All of these maps show that the soil moisture in Victoria has been drying and that in the past 25 years the research area may have had a 3 metre (H_s) depth rather than the 2.3 metre adopted by AS2870-1996. The latter was adopted from Aitchison and Richards – C.S.I.R.O (1965) and later research by the AS2870 committee. Anecdotal evidence does not support the use of H_s = 3 metre throughout the research area but perhaps varying from 2 m to 3 m travelling from east to West in the Werribee plains. It is possible that the initial TMI to *H*s relationship was too conservative, therefore further investigation is recommended.

3.2.2 Recent weather effects in S.E. Australia

The most recently published Federal census statistics show that almost 40% of Melbourne's traditional low-rise residences in the past 20 years have been built in the research area (Western and Northern suburbs). In this area the foundation soil consists mainly of high water-reactive volcanic clay. From 1997 to 2009 there was an almost continuous drought which was followed by a very wet 2 year period (2010-2011), a 2 year drought and a brief but very wet period in mid to late 2016. These conditions initially caused doming of the slabs due to the shrinkage of the foundation clay around the house perimeter followed by slab dishing at the edges in the wet period. From 2012 to mid-2016 the soil swelling recovered somewhat, but most cracked and lifted slabs, have not.

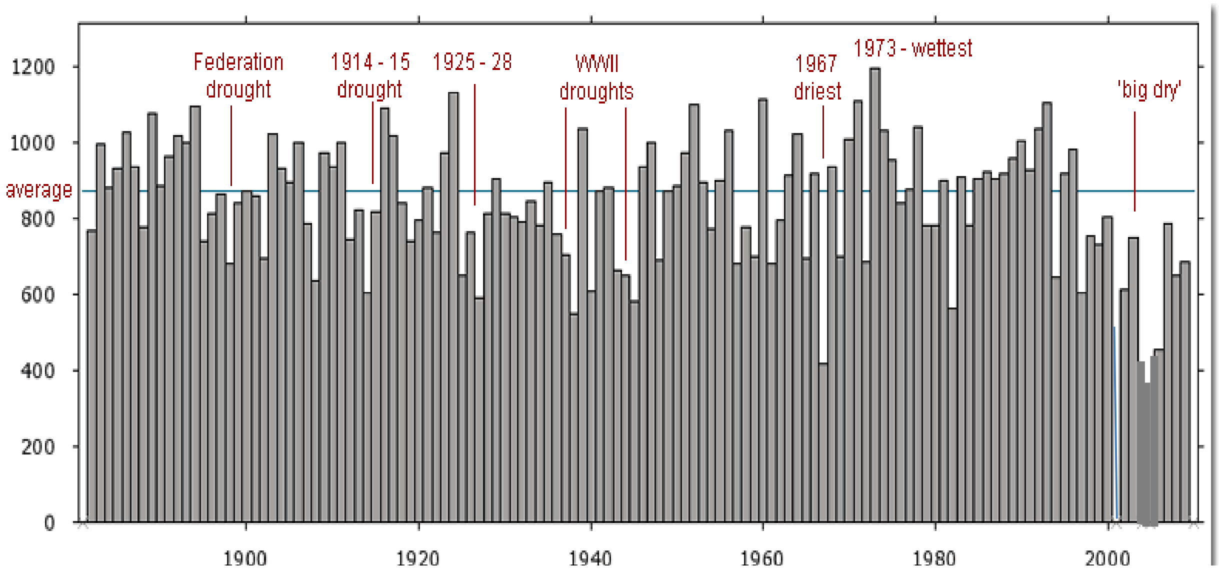


Figure 34: –Dry and wet periods in Australia (BoM on-line 2009).

BoM published the following graph describing officially nominated drought and heavy rain periods. These show that the 'Millennium drought' was more severe than the 'Federation

Drought which was the most severe recorded in the 20th Century. Since 2010 the atmospheric drying has moderated but still continues on a drying trend.

3.3 EFFECT OF CLIMATE ON RESIDENTIAL ENGINEERING.

AS2870 refers to the 'design life' of a house as 50 years. It is not clear whether this is an aim or an actual satisfactory performance period based on past performance or expected performance. Whatever the case with the on-set of climate change, it appears optimistic to expect a satisfactory performance from existing slab design models. It should also be noted that the early work on AS2870 may have been influenced by the wet periods in the 1970's.

After the publication of the new Australia-wide foundation standard (1986) some practitioners became aware of the importance of climate and clay moisture variation as influences on the performance of footings and pavements. This information is still trickling through to practitioners, designers and construction companies.

With the popularisation of slab-on-ground and waffle slab construction some issues were addressed but new ones arose, however the importance of the Australian Standard changing the emphasis from soil bearing capacity to soil reactivity should not be underestimated in the residential industry.

3.3.1 TMI and 'active' soil depth (H_S).

In the Australian Standard 2870 this index was used as a basis of determining the depth H_s and the slab edge distance. Comparisons of these parameters appear similar to those proposed for this climate in U.S.A.

The climate zones devised for figure 31 was a mixture of local climate description and TMI Isopleths and were adopted for engineering use only and for matters described in AS2870.

3.3.2 T.M.I. and CGM (y_s) model parameters.

Several TMI maps have been produced since the 1960's and Smith (1992) (personal communication) suggested that AS2870 should link the TMI values to climate areas. TMI maps and papers have used as connections to soil model parameters by a number of researchers.

The trend line of TMI values in the research area shows a continuing drying trend. In severe droughts the rate of soil shrinking slows due to higher soil suction and evaporation resistance.

The warming oceans continue to increase the atmospheric energy which is expressed in increasing temperatures and storm activity leading to longer and more serious droughts and floods.

Karunarathne et al (2015) calculated the TMI in the state of Victoria using 4 different published methods (3 of which modified the original Thornthwaite method) to compare the calculating procedure and the results. They concluded (in part):

"All of the methods show similar long-term trends however the effects of extreme events occur over shorter periods would be concealed". These authors recommend that further research is required.

"Investigate the use of the averaged TMI in footing design which has influences from both long-term climate trends and the extreme events".

This work highlights some of the difficulties in developing a workable CGM model since the 'Classification' and design are sometimes carried out some months prior to commencement of construction and, at the moment there is no professional engineering inspection immediately prior to construction.

In a repetition of recent climatic events the existing Australian Standard slab designs would not be adequate to cope with ground movement. Very wet periods following severe droughts (such that are likely to occur more often) require better foundation systems and building practises. Hence characterisation (classification) has to anticipate these changes occurring during the design life of the house, (50 years).

New findings from ARC Centre of Excellence for Climate System Science, published in *Nature climate Change* on 17th January 2016 and an excerpt in the "The Age" newspaper (inter-alia) quotes Professor Sherwood who contributed to this research:

"The rainfall in Australia is not expected to remain the same as the climate warms. With 2^0C degrees of global warming, Australia is stuck with more aridity, much heavier extreme rains, of some combination of the two. South Eastern Australia is expected to dry further while other parts may become wetter"

In figure 35, Karunarathne (2016) has back-calculated the TMI trend-line to 1945 and compared them to ground movement measured from recent research carried out in Braybrook, Melbourne.

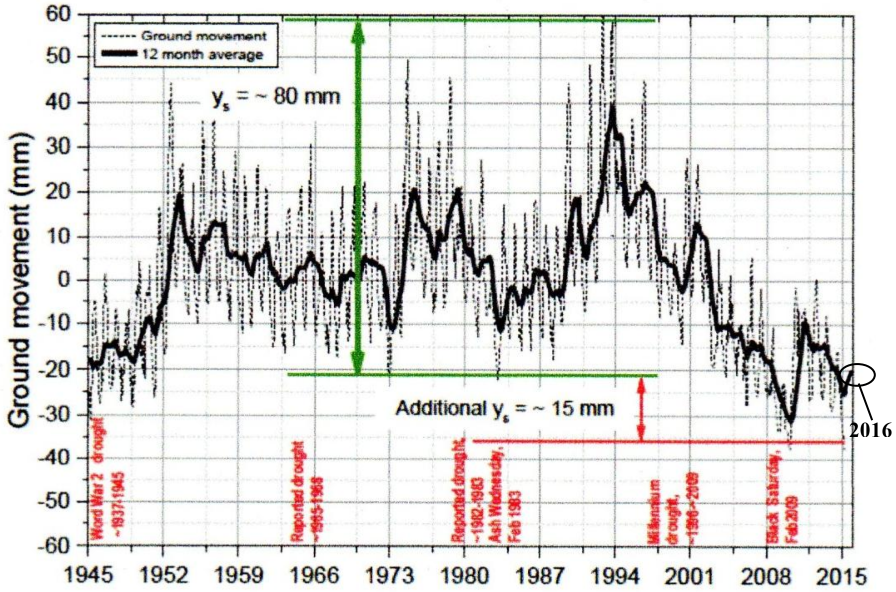


Figure 35: Ground movement based on TMI in Braybrook (Karunarathne 2016).

The trend-line in this graph strongly suggests that a severe drought such as the recent ‘Millennium drought’ caused ≈95 mm of ground shrinkage from 1994–2009 in the research site. Recent testing evidence suggests that the surficial soil suctions have certainly recovered since; however, figure 35 suggests that the deeper moistures have not reached the long-term average of the peak wet in 1994.

Karunarathne (2016) has used this and other research information to show that during the ‘Millennium’ drought the ground shrinkage increased by ≈15 mm. Also during this time there were severe water restrictions which made it difficult for homeowners to maintain their garden and foundation moisture as required by AS2870.

Changes in the TMI can affect the active depth (H_s) and the site Classification. The latest AS2870 suggests that the TMI representing the investigated area should be calculated using a minimum of 25 year of results. In anticipation of more chaotic climate, the TMI may need to be checked at more regular intervals and at each interval a running average of the previous 25 years could be used to plot the trend line. TMI has proved a good measure of soil moisture however, in changing climatic conditions it will only tell us about the past and not the conditions at slab construction stage or for the whole 50 year design life of houses.

The weather conditions experienced in the past 3 decades has provided the engineering profession the data necessary to improve the slab design models for many years to come.

3.4 Δu_s & H_S IN VARIOUS CLIMATES.

Figure 36 is a Ground Characterisation model for various climates. The H_s is based on AS2870 and research, the Δu_s on field and laboratory testing. The Δu_s and Ueq for Victorian conditions are as per TMI, literature research and research results from this thesis.

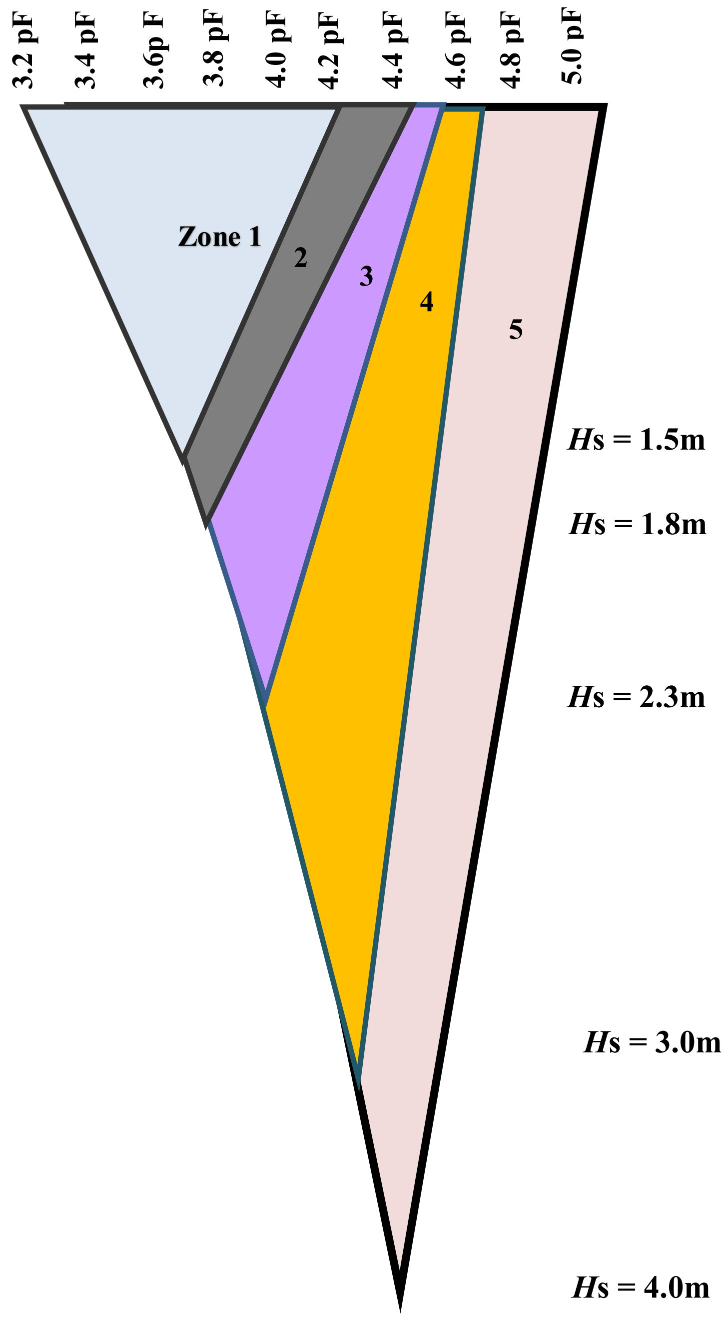


Figure 36: - Site Characteristic models for various climates.

In the past 2 decades a more chaotic climate shortened the Normal periods and increased the severity of droughts and wet periods. The Also refer Tables 9, 37, 38 and 39.

Table 9 proposes 2 extra climate zones to allow for the effect of flooding conditions in the drier areas. Zones 3(a), and 4 (a) are within their primary zones but refer to areas of flat topographies which are prone to natural inundation and have highly expansive clays. The Δu_s parameter may also be used to design for man-induced large flooding events.

Table 9: - Estimated surface suction and moisture in various climate zones.

Zone No	Climate zone name	Surface suction	Δu_s	ΔGw.
1	Alpine/Wet coastal	3.2 to 4.2 pF	1.0	35.0%-20.5% = 14.5%
2	Wet temperate	3.3 to 4.5 pF	1.2	32.5%-17.5% = 15.0%
3	Temperate	3.4 to 4.6 pF	1.2	31.0%-16.5% = 14.5%
3a	Temperate-prone to inundation	3.1 to 4.6 pF	1.5	37.0%-16.5% = 20.5%
4	Dry-temperate	3.5 to 4.8 pF	1.3	29.0%-15.0% = 14.0%
4a	Dry-temperate-prone to inundation	3.2 to 4.8 pF	1.6	35.0%-15.0% = 20.0%

Note: Table 9 is largely sourced from research papers quoted in Chapter 2 and 3 and investigation results from this thesis in Climate zone 3(a). Alternative parameters for Climate zone 4(a) are interpolated from the research. Climate zones 5 and 6 are also prone to inundation since severe river and sheet flooding is common in these parts of Australia; however these were not considered due to insufficient direct information or personal experience.

The research for this thesis has shown that the Δu_s parameter commonly used (1.2pF) was exceeded in the research area between in the past 2 decades and particularly from the end of the millennium drought (mid-2010) to the end of the ‘Wet’ period (2012). However some of the inundation effects could have been avoided by better site drainage but the remainder were climate driven.

3.5 SOIL MOISTURE CHANGES PRE-CONSTRUCTION.

The as-built foundation soil moisture in highly expansive clay sites has probably the greatest influence on future slab behaviour. (Refer figures 7 (a), (b) and (c) in Chapter 2). However the as-built condition is rarely considered in the Site classification process other than in extreme cases. Some local engineers realised this problem and exercised their expertise to stiffen the slab designs in attempt to cope with the effects of climatic and soil moisture conditions at the time. Poor site development is a major cause of post-construction ground movement and is difficult to correct. Most new suburban houses in large cities in Australia occupy up to 70% of the allotment and have very small gardens and walkways and are fully fenced on 3 sides.

Most of the new house sites in the research area are level and only slightly-higher or level-with the road gutter. This makes the pipe grade difficult to have an effective cleaning-flow. The pondage of water near houses are important factors for clay sites. These matters are discussed further in Chapter 5.

A lack of proper grade in drainage trenches causes rain, garden water or water from leaking pipes to fill the trench and flow under the slab thus lifting the edges the slab. Poor ground levels are also a common cause of bad drainage. Sites that are cut perfectly flat allow water to pool before and after slab construction. On a near-flat site the slab sub-grade should be raised by 100 mm or so to allow a slope of the storm-water trenches without relying of reducing levels of crushed rock to drain any trench water.

The climate conditions during this research period consisted of a severe drought followed by a very wet period causing edge lift. Edge lift in these conditions can be $0.5y_s$ according to Walsh or $0.7y_s$ according to Mitchell. The houses investigated were designed as per AS2870-1996 and mostly classified as 'H' hence the maximum y_s would have been 70 mm and the maximum y_m 35 mm (using the Walsh method) and 49 mm (using the Mitchell method). Appendices 1 and 2 show the movements read and a summary of these figures.

3.6 SOIL MOISTURE CHANGES DURING CONSTRUCTION.

Estimating ground movement pre-construction as per the Site Classification method in AS2870 only gives a minimum base of comparison. Conditions during construction and post-construction magnify the problem. Some of the causes of soil moisture change are natural while others are man-made. The following would need to be eliminated or considered in the design process to reduce ground movement in highly expansive clay foundations.

Natural conditions:

(i) Droughts.

(ii) Floods.

(iii) Topography of site and nearby land.

(iv) Shallow water table and aquifers.

(v) Climate and predictable changes.

(vi) Home owners' expectations.

Man-made conditions:

(i) Maintaining or planting trees and/or dense vegetation close to footings.
(ii) Ineffective ground drainage.
(iii) Service pipe drainage not capable of withstanding ground and slab movements.
(iv) Pipe drainage that is too shallow to withstand even light ground traffic.
(v) Delays in constructing or having inadequate roof drainage during construction.

In the research for this thesis there was a combination of natural and man-made conditions noted which exacerbated the normal ground movement.

3.7 SOIL MOISTURE CHANGES POST-CONSTRUCTION.

Retention or planting trees or dense vegetation in highly expansive soils can cause clay shrinkage and settlement unless an adequate catchment area and watering is established.

Neglected open ground near buildings during hot and dry seasons can cause clay shrinkage and outward rotation of any walls nearby, particularly on the corners.

Overwatering of gardens near the house footings will cause footing lift. Gravel gardens alongside house walls allow inundation but slow evaporation, exacerbating foundation movements.

Incorrect construction of concrete pavements around buildings can change the as-built environment. These pavements are rarely constructed with the proper slope. This is a particular problem in flat and highly expansive clay sites where drainage may be required to prevent discharging water to, or from, the adjoining properties. Constructing additional covered areas without roof or ground drainage can also cause localised clay swelling.

Water discharging from air conditioners particularly in humid areas, leaking services can also cause differential building movements; as can badly maintained and blocked roof or soil drains.

Deep excavations near building perimeters increase soil water evaporation during dry weather and water ingress during wet weather.

3.8 CHAPTER 3 CONCLUSIONS

The Thornthwaite Moisture Index initially came out of farming studies but is now so useful in helping to develop many engineering values. With respect to this thesis it has helped to estimate a number of soil parameters for various world-wide site characterisation models.

TMI's have provided a good historical interpretation of the interaction of surface soil moistures with weather systems. However, with a changing climate we can no longer rely on historical records, particularly for the design and construction of infrastructure founded near the surface.

The development of satellite technology we can now add daily soil information therefore designers, engineers and builders need to plan and respond more quickly to the changing foundation conditions. Predicting soil behaviour and building performance has become more difficult. Buildings need to be constructed for a continually changing environment and performance life.

The development of new techniques and products require Standards to be reviewed more regularly and stricter inspection systems put in place.

The following chapter 4 briefly outlines the Australian characterisation system which has served the industry well until the recent chaotic climate. The effects of this climate, more knowledge and better equipment has complicated the characterisation models in certain areas but has provided useful solutions.

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CHAPTER 4

SITE CHARACTERISATION AND SLAB DESIGNS.

4.1 AS2870 SITE CHARACTERISATION.

AS2870 developed the following method of calculating ‘Characteristic’ ground movement:

$$y_s = 1/100 \sum_{n-1}^{N} (I_{pt}.\ \overline{\Delta uh})_n \text{..............................} \textbf{Equation 8}$$

Where:

y_s = characteristic surface movement, in mm.

I_{pt} = instability index. (Here expressed as %)

Δu = soil suction change averaged over the layer under consideration in Pico Farad (pF)

h = thickness of layer under consideration in millimetres.

n = soil layers.

N = number of soil layers within the design depth of suction change

Σ = sum of layers.

Site characterisation is used in Australia to predict the expected foundation ground movement. The classification is expressed in ground movement ranges e.g. Table 8.

The most common Site Classification (Characterisation – Australian method) uses:

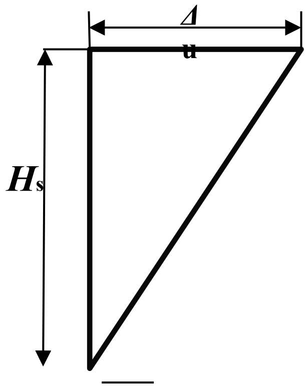
(1) Visual assessment.

(2) Profile identification (Appendix D - AS2870)

(3) Movement estimates.

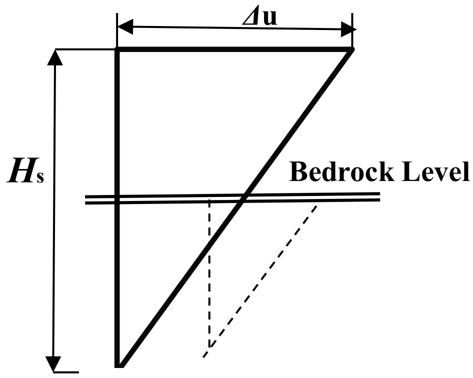
The movement estimate is (y_s) which is calculated using triangular shaped suction models in the soil profile, soil instability indices (I_{pt}) and depth of suction change (H_s). Figures 37(a),(b) and (c) are very generalised and more detailed models in chapter 4 show that the (H_s) depth varies in different climates and the suction interval at the surface is taken as 1.2pF (AS2870) although the actual values differ in each climate zone.

These figures merely indicate the effect of “truncation” to the model and the ground movement is based on the ‘active area’ of the triangle.



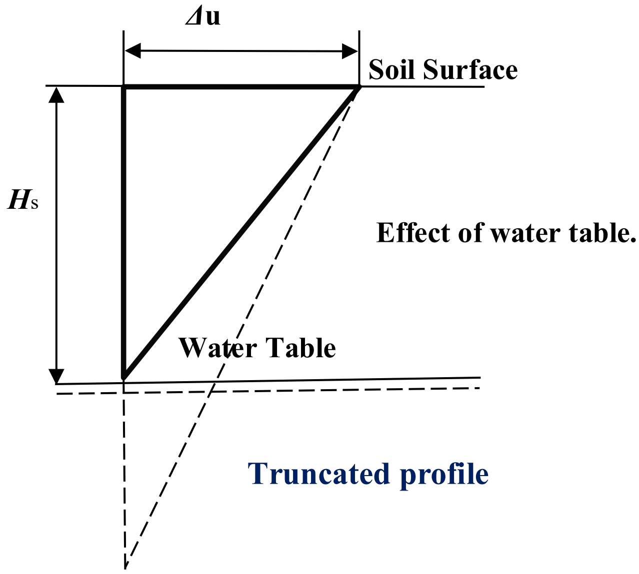
Consistent soil case, soil depth >*H*s

Homogeneous soil profile.



Effect of bedrock

Truncated soil profile.



Figures 37(a), (b) & (c) – Basic AS2870 H_s models.

Example:

In the research area the Climate Zone is 3 and AS2870 the existing surface suction interval Δu in the models below is 1.2pF. The standard suction interval for all climate zones in Australia of 1.2 pF is here replaced with graded values Δu_s The new design indicated by the research in Climate zone 3(a) is 3.1 to 4.6pF = 1.5pF. Included in the calculation of y_s is the lateral soil restraint factor (α) to allow for the higher vertical swell in uncracked soil compared with cracked soil.

The above figures are simple diagrams which introduce the basic triangular model in AS2870, however, figure 36 is to be considered to estimate the suction variations in different climate zones for more accurate calculations of soil indices and y_s.

Table 10: Classification based on site reactivity and surface movement.

Foundation	y_s in mm	Class
Most sand and rock sites with little or no ground movement from moisture changes.	-	A
Slightly reactive clay sites with slight ground movement from moisture change.	0 to$<y_s \leq 20$	S
Moderately reactive clay sites with moderate movement from moisture change.	20 to $<y_s \leq 40$	M
Highly reactive clay sites with high ground movement from moisture changes.	40 to $<y_s \leq 60$	H1
Very highly reactive clay site with very high ground movement from moisture change.	60 to $<y_s \leq 75$	H2
Extremely reactive clay sites with extreme ground movement and extreme moisture change.	$>y_s 75$	E

The methods most commonly used for Classification:

- Identification of the geological origin of the soil profiles.
- Soil profile, soil type identification and assessment or testing of the soil indices.
- Computation of the characteristic ground movement limits in terms of (y_s)

This characterisation considers the following:

(a) Climate zones and predicted slab shape.

(b) Climate and surface suction range.

(c) Idealized mound shapes.

(d) Depth of active clay.

(e) Soil layer depth under consideration.

(f) Soil Instability index.

4.2 CHARACTERISATION BY SOIL PROFILE IDENTIFICATION.

This method is outlined in AS2870 Appendix D and links soil behaviour to the mineralization of the parent rock, transportation of the eroded products, sedimentation conditions and past and present climate. AS2870 advises that this method should be limited to practitioners with local expert knowledge in soil geology. Table 11 shows the soil group investigated in the research area.

Table 11: AS2870-2011, Table D1 (in part) - Group 2 soils.

Clays derived from alkaline volcanics (basalts, pyroclastics, dolerites, greenstones) or sedimentary rocks interbedded with alkaline volcanic and pyroclastics. Including alluvial or colluvial clays from these rocks and deposits.				
Climate Zones	**1**	**2**	**3**	**4 / 5**
≤ 0.6m depth of clay over massive rock.	M	M	M	M-D
>0.6 - 1.5m depth of clay over massive rock.	M	M/H1	M/ H1	M–D/H1-D
>1.5m depth of Clay over massive rock.	H1	H1/H2	H2/E	H2-D/E-D
Deep lateritic, gravelly or coarse sandy clay	M	M	M/H1	H1-D/H2-D

4.3 CHARACTERISATION BY FIELD AND LABORATORY TESTING.

The general method of site characterisation used in Australia has a long history, however recently it has been almost standardised using the following procedures:

(a) Familiarisation with the expected geology and land use in the past.

(b) Investigating the site from recent and historical aerial views.

(c) Desk-top study of nearby earlier investigations.

(d) Drilling one or more test sites/building pad to the H_s depth or rock.

(e) Hand identification, description and depth of soil layers.

(f) Some form of moisture state identification.

(g) Soil testing using Australian standards AS1289 and AS1726.

(h) Observations of any feature that has recently, or in the future, may cause abnormal moisture conditions as described in AS2870-2011.

4.4 CLIMATE AND PREDICTED SLAB SHAPES.

The climatic changes in recent times are affecting our complex living, engineering and industrial systems. A number of scientists have asserted that at least some of the recent climatic changes have occurred due to the increase of greenhouse gases since the Industrial Revolution. In January 2015 (in a radio interview at the ABC) Dr Kevin Hennesy (Principal Research Scientist at CSIRO Marine and Atmospheric Research) stated:

"Rainfall is likely to decrease in Australia and more of it will fall during heavy rain periods. This will increase run-off and reduce the overall soil moisture".

The 'Mound' model (which is the AS2870 basis of the footing designs) is said to moderate as the soil moisture equilibrates from the edge to the centre of the slab. However this takes many years (if at all) because this process is interrupted by changes in the climate cycles. Hence while the moisture under the centre of the mound is moderating the central slab shape, the ground is either shrinking or swelling around the edges. AS2870 shows that the slab designs are based on idealised soil mounds either for centre lift or edge lift. For the Walsh method, the mound shape is taken as a flat section with movements occurring over an edge distance (e). The shape factor for edge lift (W_f) is used to define the compound parabola as shown in figure 26 (a), (b) and (c). Walsh and Mitchell proposed that the following design values for differential mound movement (y_m):

Table 12: - Effect of initial soil moisture on slab movement (y_m).

Type of slab movement and site condition	Walsh method	Mitchell method.	Average
Centre lift	0.7 y_s	0.7 y_s	0.7 y_s
Edge lift' on an initially dry site	0.5 y_s	0.7 y_s.	0.6 y_s

4.5 FOOTING DESIGN & CONSTRUCTION CRITERIA.

To achieve the best outcome AS2870-2011 emphasises the following:

- Correct classification of the site with respect to clay/water reactivity.
- Proper preparation of the building site that allows long-term good drainage.
- Footing, drainage designs and construction which suit the site conditions.
- Maintaining well-drained conditions through construction and life of the house.
- Co-operation of the involved parties, e.g.: designers, engineers, builders and owners.

4.6 CONDITIONS FOR USE OF DEEMED-TO-COMPLY FOOTINGS.

The use of deemed-to-comply footings whose basic designs are supplied in the standard are restricted to 'normal' conditions.

The site classification procedure is limited to 'normal' site moisture conditions. 'Normal' is described in AS2870 as: "Seasonal and regular climatic, building, subdivisional and normal garden conditions without abnormal moisture conditions".

Abnormal conditions include (AS2870-2011) - "Removal of existing buildings, planting or maintaining trees that will cause abnormal foundation moistures, failure to provide adequate site drainage, failure to repair plumbing leaks or causing other unusual foundation moisture conditions".

'P' (problem) sites are also excluded from 'normal' conditions and is not considered a Classification. These sites require the engineer to use engineering principles outlined in Section 4 of the Standard or other well-accepted engineering design principles appropriate to the problem.

1. Houses are designed to perform economically and adequately for the 50 year design life within the guidelines in AS2870 Appendix B and C which state (in brief):

2. The expected wall and slab performance for 'normal site conditions is described in the Scope as a low incidence of damage category 1 and an occasional incidence of category 2, (Table C 1).

   (b) With reference to accepted wall damage, Category 1 is described as Very slight with <1mm cracks and Category 2 as Slight with <5 mm cracks.

   (c) With reference to accepted concrete floor damage, Category 1 is described as very slight <1mm cracks and Category 2 as Slight with <2 mm cracks. Differential slab distortion is also considered.

4.7 SLAB DESIGN AND CONSTRUCTION ISSUES.

The most common footings used in the study area since its development, have been either Waffle slabs or Slabs-on-ground. Refer figures 11 and 12.

The waffle slabs supporting brick veneer houses have continuous slab panels which are 100 mm thick and are reinforced with orthogonal internal beams 110 mm wide of varying depths. The external beam for brick-veneer houses is 300 mm wide. The slabs and beams are poured on the surface separated by polystyrene form work. The depth of the beams and steel reinforcement varies according to the site classification.

The S-O-G have 100 mm deep concrete reinforced with 300 mm wide internal and external beams at varying spacing. These factors and steel reinforcement varies according to the site classification and the superstructure type.

4.7.1 Pre-construction issues.

Some of these issues begin at Governmental stage; such as reduction in allotment size and relaxation of regulation and inspection requirements. These have led to difficulties in protecting one allotment from the conditions or uses of another and quality of design and workmanship.

Other issues have been:

- Standards that have not kept up with recent climatic conditions
- Over 50% of houses built on dry highly expansive clays
- Under-engineered house construction.
- Building boom and lack of well-trained skilled staff and contractors.

4.7.2 Mound heave (centre lift)

Initially the Australian slab design was based on 'mound heave' (centre lift) and this was expected to be the long-term shape and best design model. Improved models were later developed by Walsh and Mitchell and entered in the Australian Footing Standard (AS2870).

The author's experience is that true mound lift in Melbourne climatic conditions have been very rare in the past 3 decades and only found where plumbing or badly constructed trenches allow water to ingress under the slab. Other reasons preventing a true centre lift shape may be:

- Water ingress to the centre of a house slab by clay suction requires a long wet period which has not occurred in the recent past.
- Water diffusion in the highly cracked soil column reduces the accumulation of water in the surficial layers directly under the house slabs. Judging from the slab shapes and contours this moisture spread may not have reached the centre of the slabs. (Refer Appendix 5 and 6.
- Each time the climatic conditions reverse the slab shapes changes and if the transitional period is short after a wet period the process of centre heave is reversed and if a drought follows, the edge of the slab returns to a concave shape.
- In some climates however there may be an accumulation of centre lift over many years.

AS2870 advises about any work that may change the site soil suction which could void the Characterisation made prior to construction. e.g.:

- Site preparation and excavations or filling may change the moisture and structural integrity of the foundation soil and hence the Site Classification.
- Many parts of the construction process have the potential to change moisture condition of the foundation soil and increase the surface suction variation (Δu_s)
- The home owners can also have a significant effect on site moisture during landscaping, excavating for pools and various water discharges or plantings.

4.7.3 The as-constructed foundation moisture.

TMI in an area can alter the 'active depth' of the soil moisture and suction and therefore may affect the classification of a site. The latest AS2870-2011 suggests that the TMI of a building area should be calculated using a minimum of 25 year TMI results. The TMI is based on past average and may be useful in determining the average depth of moisture change (H_s) however it tells us very little about future climatic conditions.

Figures 8(a) and (b) show the effects on ground movement under a slab which experiences different soil moisture conditions in its life. The strain in the relevant suction change is much lower in drought periods than in wet periods. (Refer Appendix 5).

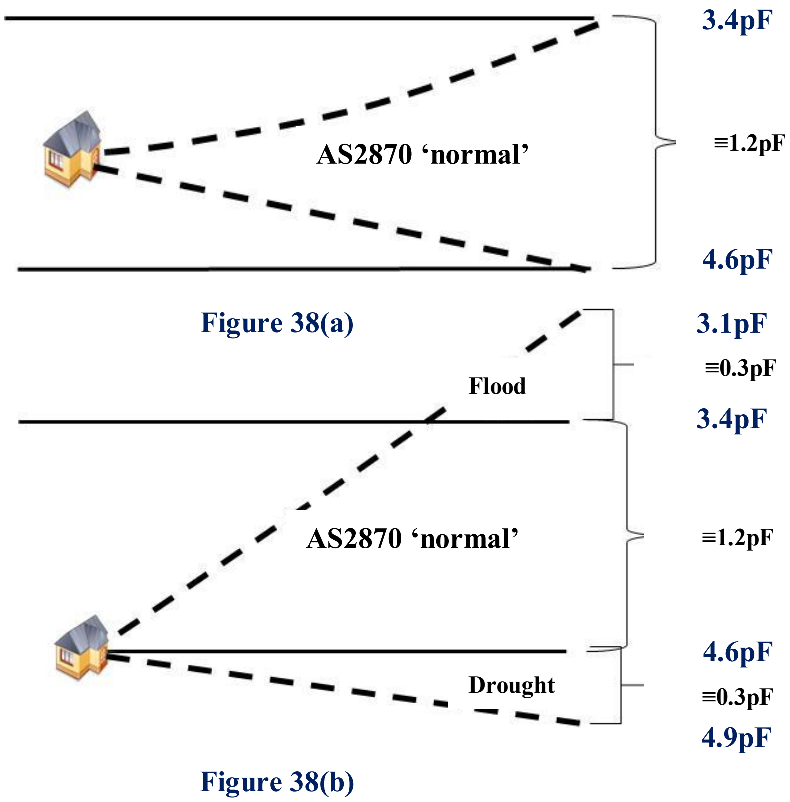


Figure 38(a) & (b): - Suction variation under slabs in different climate conditions.

Figure 38(a) shows that a house built in benign soil moisture conditions will experience a surface suction variation of ≈1.2pF and the slab distortion (y_m) will be roughly equal in both directions. However a slab built in drought conditions followed by flood will have considerable 'edge-lift'; figure 38(b). Although in some cases a mound shaped slab may develop in natural conditions by lateral moisture ingress under the slab; settlement or lifting of the edge are much more common. Edge-lift is also usually more severe since the suction/strain trend line is steeper in the suctions

4.7.4 Issues arising from construction in wet after a severe drought.

The issues that cause the most problems occur during construction and are mostly related to soil wetting or drought conditions. Building in drought which is immediately followed by a wet period appears to be the most problematic however these conditions are exacerbated by many factors.

Example:

1. Inadequate site characterisation techniques.
2. Extreme weather conditions.
3. Building the slab on a site which is flat or slightly saucer shape.
4 Placing incorrectly sloped porous soil around the slab and preventing rain water to flow away from the house. (Figure 40)
5. Leaving the house site in a poorly drained condition which will require substantial work to rectify.
6. Leaking water from unconnected down-pipes during or post-construction and concentrating water in 6-8 spots around the house.
7. If there are insufficient down-pipes, roof gutters will overflow for the life of the house.
8 Leaking underground plumbing during or after construction due to damage or pipe joint inflexibility.
9. Post construction changes such as poor landscaping, incorrectly drained paving or sheds, overwatering or lack of watering and changes in neighbouring properties.
10 Allowing trees to remain too close to the house or not up-grading the footings to cope with their effect. AS2870 offers some guidance about trees in Appendix H and Commentary.

11 Many cases of 'poor drainage' were found to be the non-adherence to figure 40 (AS2870). The most common fault found was the flat slope in area 'A' which allows water to pool against the slab and gradually find its way under the edges of the slab.

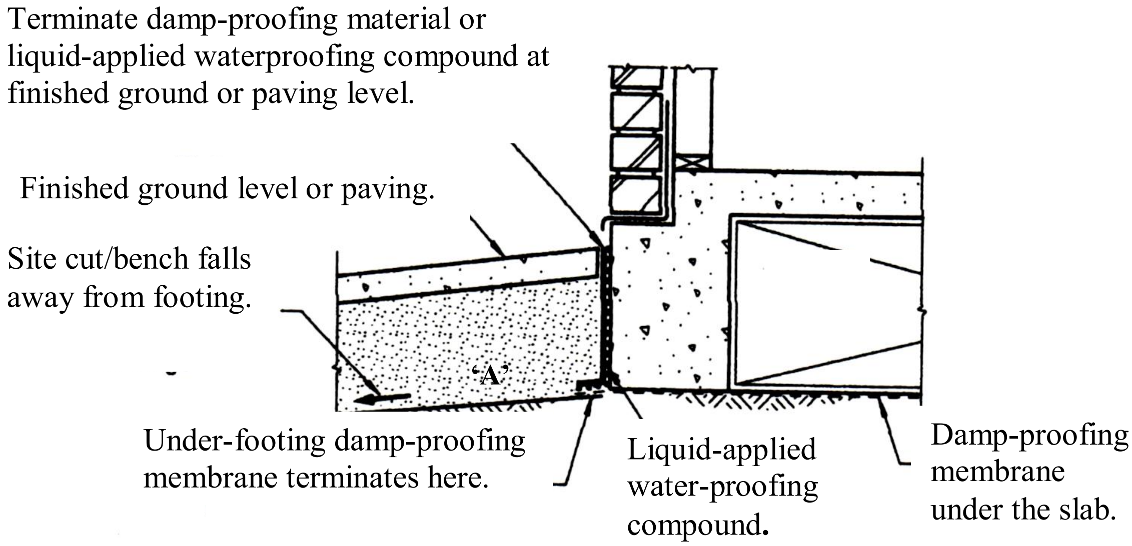


Figure: 39 – Perimeter protection of waffle slabs. (AS2870)

Some of construction issues arise from poor building practises from the builder; such as leaving the surrounds of the house level or sloping negatively towards the house. The main problem being that to create a slope away from the house, most builders place, improperly compacted, fill around the perimeter beam and often at an incorrect slope. (As distinct from figure 39)

Apart from the fact that this fill is usually porous, it drains on to a surface that is either flat or sloped towards the slab. A correctly constructed slope away from the slab is required to meet the Standard requirements and avoids many problems for owners in the future.

The importance flexible joints in the PVC service pipes (as recommended in the Standard). Is often ignored. These have been found necessary to avoid leaks in highly expansive clays.

Where the pipes emerge from the slab an appropriate 'lagging' is to be used to seal the pipe the surrounds. Where the pipe trenches have insufficient grade a tamped clay plug should be used where they cross the slab edge beams to prevent water from flowing under the slab.

Service excavations running close and parallel to the footings are to be avoided to prevent water penetrating under the slab.

4.7.5 Post-construction issues.

Owners are given certain responsibilities in maintaining the so called normal site conditions to achieve the design performance of the house. Such as:

(a) Not allowing the growth of trees or dense vegetation too close to footings.

(b) Not to remove trees without re-moisturising the ground to the as-constructed moisture.

(c) Not constructing house perimeter paving without an inadequate slope.

(d) Preventing irregular or over-watering of gardens adjacent to the house.

(e) Maintaining effective site drainage.

(f) Failure to repair plumbing leaks as soon as detected.

(g) Constructing additions or garden sheds which discharge water near the house.

In many cases these requirements are very restrictive and not easy to maintain for the life of the house particularly when the owners or occupiers are away for any length of time, or when ownership changes.

4.8 CHAPTER 4 CONCLUSIONS.

The research has shown that more irregular climates require much better construction practices. The restrictions in the Scope of the Australian footing standard (2870) have attempted to keep house construction costs to a minimum, however many designer, builders and owners have not fully understood the implications and did not follow all these restrictions.

Clearly many changes are necessary, however the most important is the reduction of moisture variation in expansive clays e.g.:

- Better subdivisional designs to suit soil conditions.
- Better site drainage.
- More accurate ground movement predictions.
- Allowance for inundation conditions in footing designs.
- Better training for all participants.
- Better information for owners.

Chapter 5 following, discusses the laboratory and field work carried out to determine the design parameters which may suit the recent chaotic climate and soil moisture changes.

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CHAPTER 5

LABORATORY & FIELD INVESTIGATION & RESULTS

5.1 IDENTIFICATION OF SMECTITE CLAY TYPES

5.1.1 Colour, plasticity and inclusions as identification indicators.

Although the CCS test is relatively simple, a good understanding of soils, their colour, plasticity and inclusions can be a great help in determining the timing of each testing stage. These properties form part of the test and are also recorded for future reference.

Colour in a particular soil province can be an indicator of plasticity and soil type but is not conclusive. The investigator is encouraged to carry out the following field tests when necessary. In the case of light grey or whitish basaltic clay a drop of acid will distinguish Montmorillonite or Kaolinite from Calcrete; the first two do not react very much whereas the Calcrete will fizz. The most common colour base was in the samples tested was brown which was mixed with various amounts of red, grey and an occasional orange mottle. The Calcrete is white, off-white.

Montmorillonite can also be easily distinguished from Kaolinite with a few drops of water. The latter has very little plasticity whereas the Montmorillonite becomes very sticky. There are grey clays which have locally been called 'Keilor grey'. These were first recognised in the original township of Keilor as being highly expansive and have a high Montmorillonite content. The grey colouring is mostly from a type of Montmorillonite with calcrete and/or sand and silt. A closer tactile examination and wetting of the sample easily identified these components.

Another common clay colour in the area is red; often this colour is due to the presence of ferric ions. These clays can be easily identified by the grittiness in the mouth and some may be 'Ferricrete-clays' which have a lower plasticity. Many of the clays in the research area also contain Aeolian sand and silt blown in from the arid areas to the West and in-filling the cracks in the clays. Good examples of all these clays were found in the Melton area.

The presence of silt in a soil can be recognised by holding a moist disc of the soil in the palm of the hand and continually tapping the underside of the palm; those with silt content will develop a shiny surface. The ease with which this can be achieve is a good guide to silt size or content.

The calcrete is often found as grey layers or as a 'grain-like' smattering through the clay, clumps and fillings of fracture planes in the clay or rock and sometimes as a coating on core stones or massive rock. It was difficult to discern a pattern in the deposits of the calcrete layering but it most likely deposits in response to pH in the soil. Clays with Ferric iron in the Melton area had a more open fabric and are less plastic than nearby less ferruginous clays. The average I_{ccs} in these samples was 5%.

The soil colours in the research were described in the moist state in the laboratory after the samples were 'conditioned' to the initial test suction state. This helped standardise a number of factors as well as the colour description.

5.1.2 Shrink/swell processes in soil.

Sorochan (1991) stated (in summary) that the expansion of soil occurs during its interaction with water (or other fluids) and is governed by primary and secondary phenomena.

Primary Phenomena:

(a) Process of penetration and bonding of water in the void space between groups of particles in the crystalline lattice of the mineral.

(b) Process of bonding of water at the demarcation of solid and liquid phases.

(c) Processes occurring in the pore fluid in the soil (Osmotic suction).

Secondary Phenomena:

(a) Hydration of exchangeable cations.

(b) Capillary effects due to molecular surface phenomena at the interface between solid and liquid phases.

These 5 interactions of fluids and clay particles in the swelling process and are presumed to occur in the reverse order during shrinkage, however, each of these occur in overlapping stages complicating their prediction.

Neither can be represented by linear graphs with the possible exception of ≈3 to 4pF

As suggested by Fredlund et al (2010).

5.2 CALCULATING (y_S).

The most significant parameters to calculate the Characteristic Ground Movement (CGM) on a site is the surface suction variation (Δu_s), the Instability Index (I_{pt}) of the soil and the active depth (H_s), otherwise known as the moisture variation depth.

The author has adopted the values from the literature research and test results as follows:

- Normal surface suction design (Δu_s) for Climate zone 3 = 3.4-4.6pF = 1.2pF.
- New surface suction design (Δu_s) for Climate zone 3(a) = 3.1-4.6pF = 1.5pF.
- $(I_{pt}) = I_{ccs}$ x α.
- H_s = 2.3 m.

The recommended y_s model for inundation-prone sites also has a solution for the curvilinear relationship of shrink/suction.

5.3 CONDITIONED CORE SHRINK TEST.

The Conditioned Core Shrinkage (CCS) test used in this research is proposed as an advance on the Core Shrinkage Index test (I_{cs}) as per Australian Standard 1289-1998 clause 7.1. The CCS was devised by the author to eliminate the issues that arise when testing samples in different climatic and weather conditions with variable initial moistures and to avoid the variation of shrink and swell paths. This test is performed as described in Appendix 4.

All the samples were highly plastic Quaternary age basaltic clays sampled from the research area during 2014-2015.

The sampling climate conditions were of no importance since all samples were conditioned to suctions 3 to 3.5pF before commencing the shrink test.

'Figure 40
Trimming samples 'A' & 'B'
prior to conditioning.

Figure 41
Wrapped samples 'A' & 'B'
ready for conditioning.

Figure 42
Discarding ends of conditioned samples.

Figure 43
Weighing sample 'B' for moisture while testing sample A for suction.

Figure 44 –
Suction sample ready for trimming and placing in a psychrometer dish.

Figure 45. –
Placing test sample in WP4C psychrometer for total suction measurement.

5.3.1 Shrink/suction graphs.

The graphs in Appendix 5 were limited to 4 suction points and the trend-lines were drawn using Excel polynomial order 3 or 4. <u>The author stresses that this method is only used to create a line of best fit and not to represent any fixed mathematical properties.</u>

The suction range used in the shrink/suction tests for this thesis is mainly in the "Transitional and "Plateau" phases of the sigmoid curve i.e. ≈3–7pF. The "plateau" end of the curve begins at suctions >4 and the "transitional" (almost linear) at ≈3-4pF.

These curves give different soil instability index and y_s values than those calculated from the shrink/swell test in AS1289 and AS2870 (which use a 'floating' linear range of 1.8 pF). Testing has shown that the suction range >4pF is not linear and gives lower soil indices.

Figures 46 and 47 have been drawn to demonstrate the changes of the soil indices in highly expansive clays in the drier climates. In figure 46 i.e. climate zone 2 the I_{ccs} = 7.4% at 3.3-4.0pF and 4.0% at 4-4.5pF; however in the drier climate zone 4 (figure 47) it is 6.4% and 3.3% respectively (The total Δu_s used in each case is 1.2pF as in AS2870-2011).

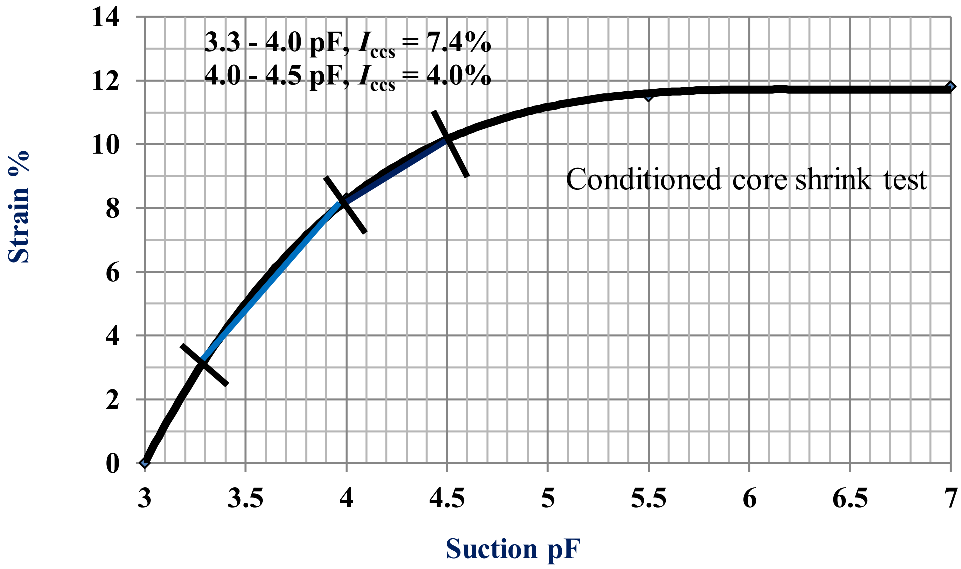

Figure 46: - Linear interpretation of the I_{ccs} shrink curve in climate zone 2.

For the Wet Temperate zone 2 the TMI = 10 to -5.

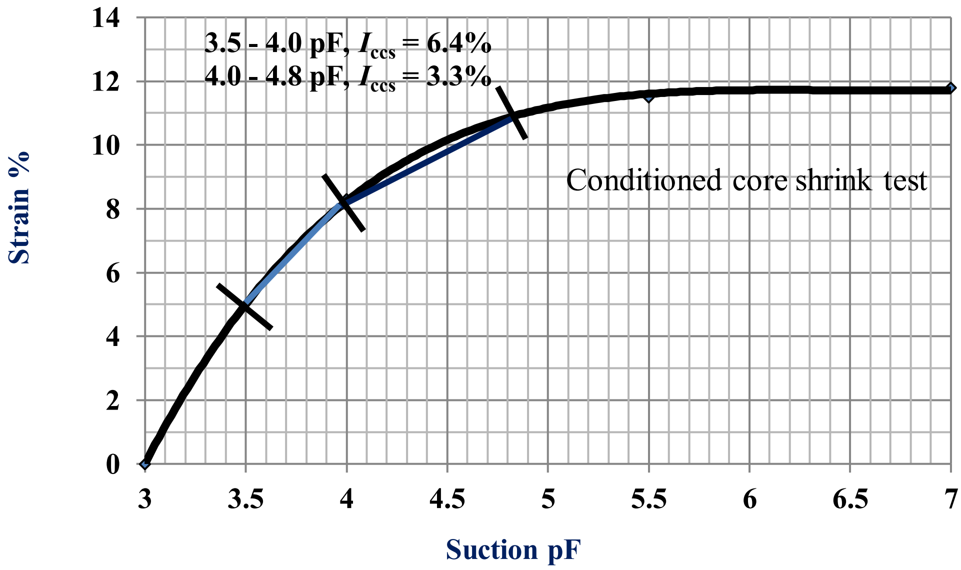

Figure 47 - Another linear interpretation of the I_{ccs} shrink curve in climate zone 4.

For the Dry Temperate zone 4 the TMI = -25 to -40.

The shape of this curve is typical of the highly expansive Smectite clays derived from the weathering of Quaternary age Basalt lavas and pyroclastics. The curve is not so pronounced in clays that have substantial inclusions which reduces their plasticity. The plateauing of the curve at suctions >4pF reduces the shrink index in the drier climates but not as much as the increase of the H_s depth in the drier climates.

5.3.2 Advantages of the CCS test to establish reliable soil indices.

Laboratory tests are rarely able to mimic the soil behaviour in the field. Soils, in particular, have too many variables therefore most tests aim at being comparable to each other rather than identical to field behaviour. In the past, psychrometers were expensive and difficult to use whereas the one used for this thesis is simple and reliable at suction ranges most valuable to the residential geotechnical engineer, i.e.:3 – 6pF.

Only the shrink test has been used in the CCS tests to avoid the estimated factors in equation 3. The shrink test is not conjoined with the swell test and is always started in a similar very moist condition. The program used to draw the curve of best fit has been excel, polynomial order 3 or 4 is. The SWCC graphs were drawn with polynomial order 3.

The SWCC together with the field soil moistures tested allows a good estimate of the near-surface suction values (Δu_s). All the CCS and SWCC test results are shown in Appendix 5.The SWCC were drawn by using the moisture weighed contemporaneously with the suctions CCS tests.

The CCS test requires a psychrometer to read suctions at a few shrink points and construct a graphical relationship over the actual site suctions and not rely on an unmeasured 'floating' field suction range of 1.8 pF in an assumed linear shrink/swell/suction relationship. The CCS compares only shrinkage with suction and not a mixture of shrink and swell with suction thus avoiding the lengthy process of the loaded (25kPa) swell test. This load limits the swell but does not represent all the field load conditions.

5.3.3 Conditioned core shrinkage test results

As part of this thesis 36 Shelby tube samples were sampled from virgin sites in the Werribee Plains area in 2014-2015 and tested using a modified Core Shrinkage test as described in Appendix 5. Graphical plots were drawn and I_{ccs} and y_s calculated. It was noted that at the dry end of the curve (>4 pF) the relationship flattens out towards the horizontal, whereas at the wet end (3 pF) it is near 45°.

This is in agreement with reports by local practitioners that there were many more houses affected during and after the wet periods than during the Millennium drought. The shape of the graph indicates that there is more ground movement per pF suction change in wet conditions than in dry. Also as the soil dries, the suction increases and requires more atmospheric influence to continue drying and finally reaches a point when the soil suction is greater than the atmospheric effect and no further drying occurs. Refer appendix 5 and 6.

5.3.4 Field moistures.

Field moisture results have been collected over the past 10 years from surficial soils and recorded and grouped in three climatic conditions, drought, wet, & transition. These moisture results were sourced from 'R. I. Brown', 'USL Group', 'J.M. Fieldwork' and 'Structural Works', were sampled at a depth of 300 to 700 mm and tested for gravimetric moisture. Accompanying reports contained a detailed description of the soil profile and surrounding conditions. Appendix 3 lists the moisture test results that were collected from 'normal' conditions. Table 12 is summary of the climatic conditions.

Table 13: - Dates and climate conditions at sampling stage.

Dates of sampling	Climate period	Comment
1997 to 2009	Millennium drought	Record drought
2010 to 2011	Wet	Record wet El Nina
2012 to 2014	Transitional	-----
2014 to mid-2016	Drought	Dry El Nino

The transitional period was short and followed a record 2 year wet period, therefore the soil moisture at sampling stage may still have been under the influence of the deeper and wetter clays. The term Transitional, describes the short period between the 'wet' and El Nino' period (2012-2014). Moisture results collected from forensic investigations carried out by Brown et al were plotted in figure 50.

5.3.5 Surface suction (Δu_s) for inundation-prone areas.

The CCS curves were drawn with Excel, exponential trend-line, order 3 or 4 to have the 'best-fit'. The moisture values were calculated by weighing the 'A' sample at each suction point. The surface suction was calculated for Normal ($\Delta u_{s\,=}$ 3.4-4.6pF) and 'inundation-prone' conditions (Δu_s = 3.1-4.6pFfor climate zone 3(a), refer Figure 49.

5.3.6 Soil-Water characteristic curves.

The SWC curves were drawn from 36 samples collected from the suburbs of Braybrook, Melton, Melton South, Plumpton, Point Cook and Tarneit at depths varying from 300–1,600 mm. The testing period lasted from 2014 to 2015. Curves were drawn with Excel, polynomial trend-line, order 2 or exponential (lines of best fit). Moisture values were calculated by weighing the 'A' sample at each suction point tested in the 'B' sample in the CCS tests.

The findings of this research shows that whichever results were chosen the suctions which occurred in the building sites greatly exceeded Δu_s of 1.2pF. Causes other than climate were prominent:

- Poor site preparation.
- Poor or delayed plumbing.
- Poorly drained landscaping.

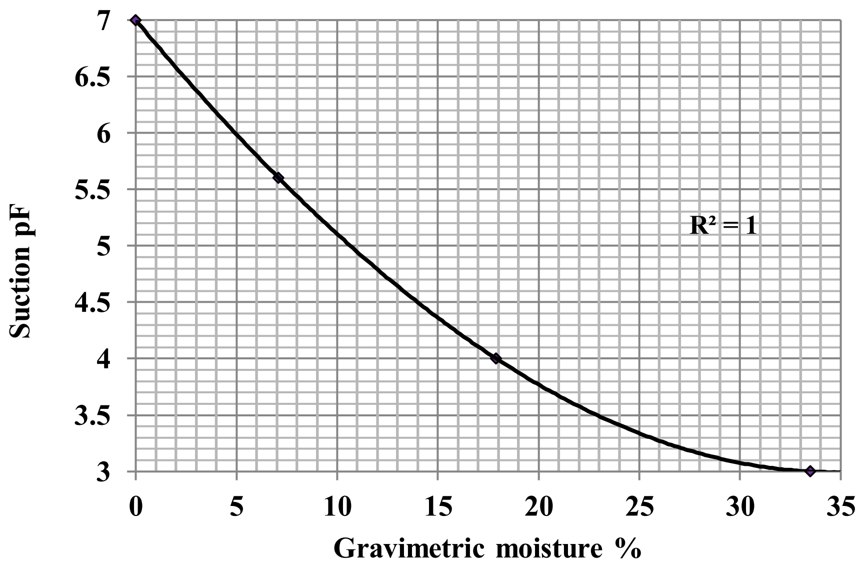

Figure 48: - Typical SWCC.

By weighing the test samples at each suction test, SWCC graphs were drawn and used to link 3 parameters i.e.: I_{ccs}, Δu_s and moisture.

The CCS, SWCC and field moisture results were used to establish the new recommended range of Δu_s. (Table 14, P. 102).

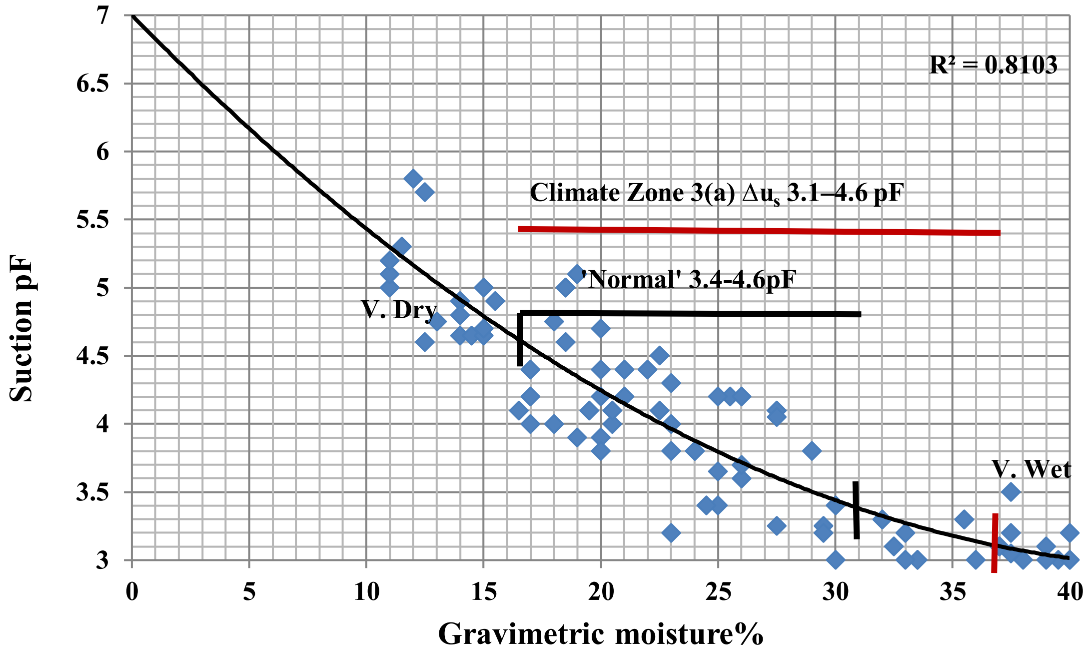

Figure: 49 – Grouped SWCC test results.

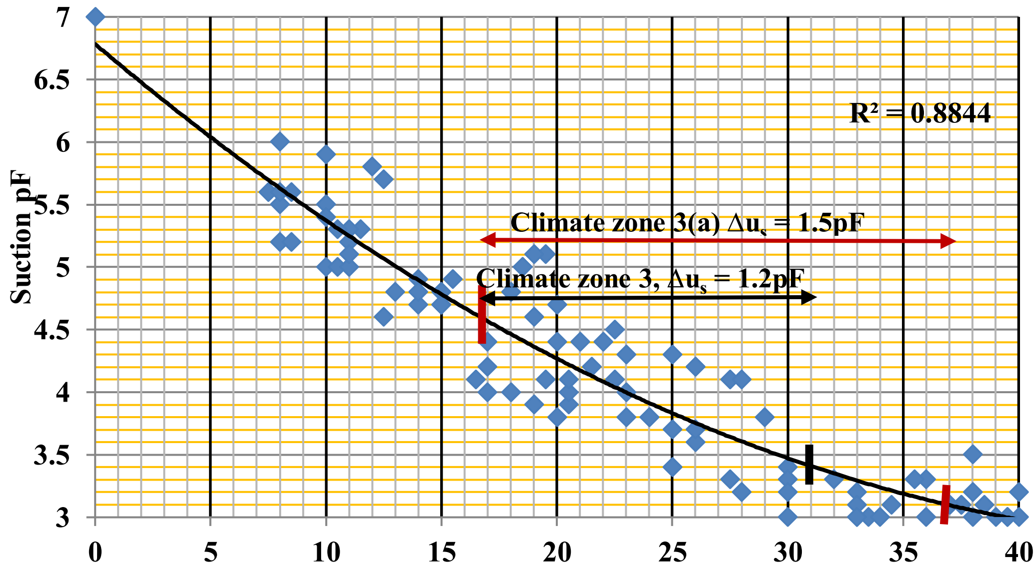

Figure 50: Grouped moistures from Brown et al and suctions from SWCC.

The sites with the following conditions were not considered in the moisture survey:

1. Free surface water near test hole(s).
2. Recent heavily watered nearby garden.
3. Nearby pipe leak detected.
4. Calcrete content or layer nearby.
5. Recent heavy rain.

6. Poor drainage around sample point.
7. Densely populated older developments.
8. Soil which was laid down as fill.
9. Soil with multiple roots.

Table 14: - Suction and moisture parameters from field and laboratory tests.

Zone 3	Grouped SWCC & CCS	Δu_s = 3.4–4.6pF = 1.2pF	ΔGw = 31-16.5% = 14.5%
Zone 3	Field moisture tests	Δu_s = 3.4–4.6pF = 1.2pF	ΔGw = 31-17% = 14.0%
Zone 3(a)	Grouped SWCC & CCS	Δu_s = 3.1-4.6pF = 1.5pF	ΔGw = 37-16.5% = 20.5%
Zone 3(a)	Field moisture tests	Δu_s = 3.1 4.6pF = 1.5pF	ΔGw = 37-17%-= 20.0%

The author has drawn the Δu_s in Table 13 in line with the results in figure 49 and 50. The average ΔGw for climate zone 3(a) using figure 49 was found to be 20.5%. The average ΔGw for climate zone 3(a) using figure 50 was found to be 20%. The moisture results were from several different sites and practitioners but from similar soil types all taken during the research period.

Table 15: - Δu_s for new model parameters for various climate zones using figure 49.

Zone No	Zone name	Surface suction	Δu_s	Gravimetric moisture SWCC & CCS
1	Alpine/Wet coastal	3.2 to 4.2 pF	1.0	35.0% - 20.5% = 14.5%
2	Wet temperate	3.3 to 4.4 pF	1.1	33% – 19% = 14%
3	Temperate	3.4 to 4.6 pF	1.2	31.0% – 16.5% = 14.5%
3a	Temperate-inundation prone	3.1 to 4.6 pF	1.5	37% - 16.5% = 20%
4	Dry temperate	3.5 to 4.8 pF	1.3	30.0% - 15.0 % = 15%
4a	Dry temperate inundation prone	3.2 to 4.8 pF	1.6	35.0% - 15.0 % = 20%

Using both figures 49 and 50 show that the moisture variations was ≈20% for inundation-prone land and ≈14-15% for land in 'Normal' conditions. Hence it can be argued that Δu_s = 1.2pF may be a good representation of 'Normal' conditions, however Δu_s of 1.5 – 1.6pF is needed for inundation-prone land with expansive soils in the drier climates.

5.4 SURFACE SUCTION (Δu_s) FOR PRONE-TO-INUNDATION AREAS.

Even though an effort was made to exclude the moisture values from the data provided where water leaks, garden neglect, overwatering or poor drainage were detected, the research findings show that the AS2870 normal moisture range was exceeded in a significant number of houses which had no obvious abnormal conditions.

The normal Δu_s of 1.2pF was greatly exceeded during the research period and most climate forecasters accept that these climate conditions will be repeated or even exceeded.

If the conditions experienced during the research period are repeated in the expected design life of houses, even a Δu_s 1.5pF will be insufficient. Therefore if the water/soil risk factors created by the builder or owners are not eliminated the new Δu_s models will need reviewing. This is undesirable since it would unnecessarily increase the cost of many houses if the advice in AS2870 is followed.

The Δu_s in climate zone 1 and 2 could be reduced as in Table 13 but will need more investigation in the drier climates.

5.4.1 Recent causes of wetting of foundation soils.

Wetting of the foundation soil, especially after drought conditions caused the greatest movements in the research area, however this wetting was exacerbated by poor drainage and construction practises and therefore its effect could have been reduced. The following are some of the most common examples of improvements in building practise:

1. Poor soil drainage, underground and unconnected down-pipes leaks.
2. Poor site preparation creating a flat or dished site.
3. Not using flexible pipe joints to cope with ground movements in expansive clay.
4. Excavating pipe trenches by excavating them with a flat base.
5. Not using clay plugs where the pipe trenches emerge from under the slab.

The above matters are well-covered in AS2870 except for the flood conditions that followed the severe drought. These conditions are expected to occur again and possibly more often in flat land and a greater problem in drier climates, however, it is not possible to totally protect all houses from these conditions without substantially increasing costs in general. The author is proposing a variation of design Δu_s specifically for house sites that could be prone to inundations climate zones 3, and 4 and recommends further investigations for these conditions in zones 5 and 6.

5.4.2 Recent causes of drying of foundation soils.

- Severe droughts.
- Lack of garden watering.
- Vegetation inappropriate for the conditions.

The last drought was very severe and accompanied by strict water restrictions with regards to garden watering, however, a large desalination plant and changes in the water distribution system since may have solved the water shortage problem for many years.

5.5 CHAPTER 5 CONCLUSIONS

The moisture results collected during the millennium drought and the wet period following have convinced the author that there is a need to extend the suction range to protect houses from flood and drought conditions in flat sites.

The comparison of suctions and moistures using figures 49 and 50 show that in 'Normal' conditions (climate zone 3) the moisture variation was approximately 14%; however, during the research period it was 20% (6% wetter). To allow for this extra moisture the surface suction in the new model would be 3.1-4.6 (1.5pF).

Using this Δu_s (1.5 pF) and the new model (which allows for the curvilinear relationship) the y_s would typically increase by approximately 25% i.e. approximately one classification higher than for $\Delta u_{s} = 1.2$pF.

The following chapter 6 summarises and discusses the investigation of 84 house carried out by the author (USL Group) and Structural Works.

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CHAPTER 6
HOUSE INVESTIGATION RESULTS

6.1 SUMMARY OF SLAB DEFECTS.

(Refer Appendix 1 and 2 for a detailed performance summary).

Part of this research consisted of forensic investigations of 85 houses designed to determine the extent and cause of slab movement during 2010 – 2013. (Refer Appendix 3)

These investigations consisted of:

- Recording the site geology.
- Inspecting the house surroundings and measuring degree of damage.
- Inspecting house interiors and assessing degree of damage.
- Interviewing the owner particularly to establish time scales.
- Checking aerial and other available photos in the construction period.
- Testing the soil profiles and their relevant properties (Clay-Water and reactivity)
- Inspecting roof truss construction.
- Measuring floor levels and contouring same.
- Reporting on findings, cause of damage and recommend remediation.

6.1.1 Floor and wall performance design aims.

With reference to external brick walls (AS2870 Appendix C), states that cracks up to 5 mm wide either singly or in nearby groups are acceptable. Cracks 50% wider in easily repaired internal clad partitions are also accepted.

Allowance for cracks in the concrete floor is 2 mm and the deviation in excess of 1/150 is undesirable.

For design purposes of articulated brick veneer houses (by far the most common type of construction in Australia) the maximum footing design deflection measured as a cord from the extremes ends of the slab is L/400 with an absolute maximum of 30 mm for a floor length ≤30m, however heavier slab mesh reinforcement is required for slabs longer than 18 m.

The design value for the differential mound movement (y_m) varies from $0.5y_s$ - $0.7y_s$ according to Walsh (1996) and $0.7y_s$ according to Mitchell (1996) with a 40% reduction for thoroughly wet profiles at the time of construction.

Strong anecdotal evidence suggests that many home owners the author find these concepts difficult to understand and too restrictive. They generally expect a crack-free house and be able to freely use and develop their house and garden as they wish. A high percentage of new home owners demand that their builder fix movements and damage even if it is within the Standard limitations.

6.1.2 Typical slab movements.

Figures 51, 52 and 53 are some examples of typical movements as measured in the damaged houses investigated. The full data is in Appendices 1 and 2. The slab contours were measured, with approximately 30 spot levels in each house, using a gas-filled 'Zip' level usually starting at a date point where the slab is least thought to have moved from the as-constructed levels.

The cross sections drawn are placed across the contours in the direction of the movement. Particular attention is given to parts of the house that have >30 mm changes in floor levels. For this type of construction AS2870 design criteria for the slab is to have a slope of ≤1:400.

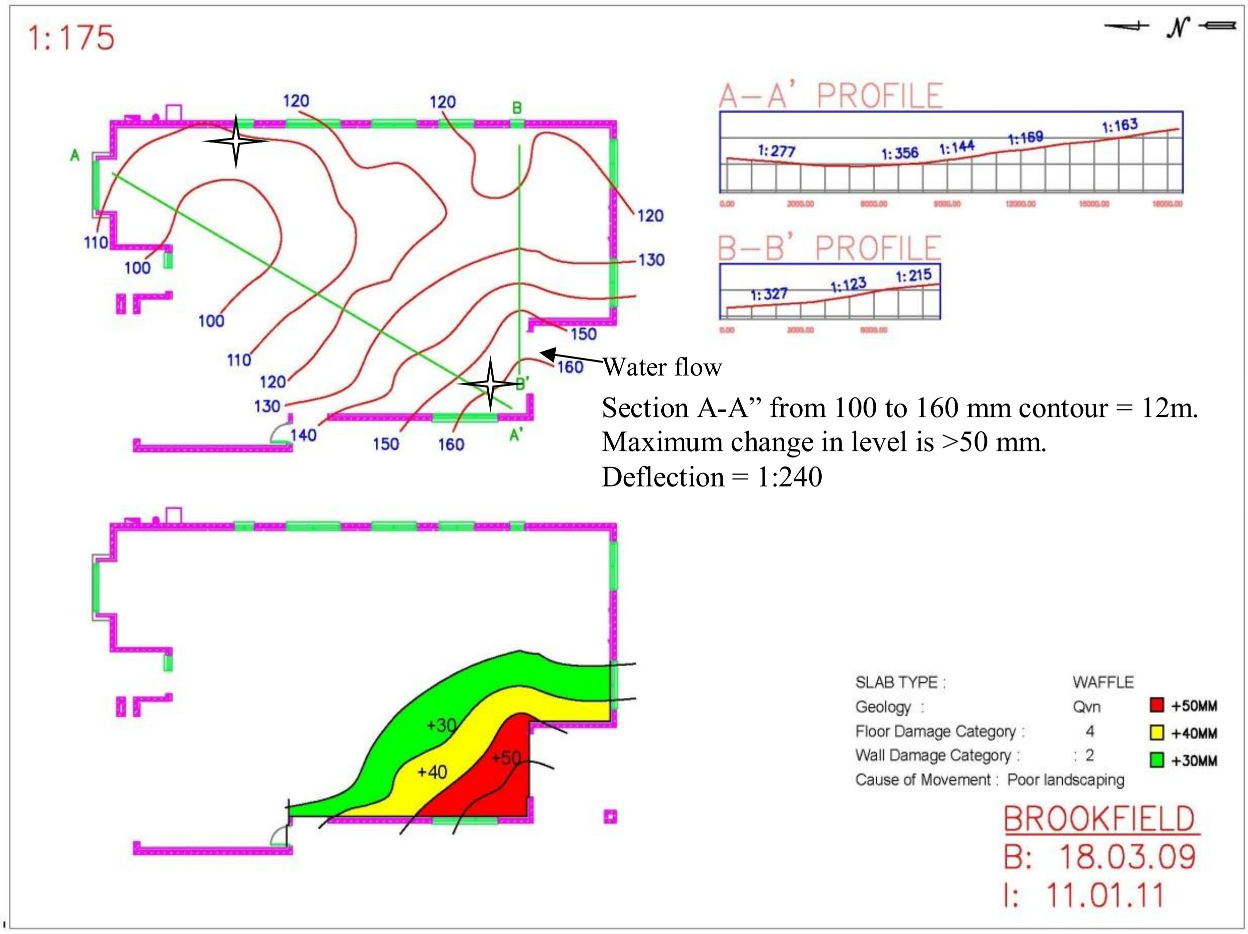

Figure: 51 – Waffle slab with corner lift, Brookfield, Melbourne.

Comments:

1. This waffle slab lifted in the rear SW corner due to pipe leaks.
2. The contours show that only the front $^{1}/_{3}$ of the slab was unaffected.
3. The coloured area shows the part of the slab that has lifted **>30 mm.**
4. The foundation soil around the coloured area is **>>PL.** (high moisture)
5. The foundation clay is considered abnormally wet near the SW corner.
6. The lift is **>50 mm** on the rear South West corner of the house.
7. The floor damage was category **3** – (Moderate as per AS2870)
8. The wall damage was Category **2,** (However, plaster wall repairs had been carried out only a few months prior to the investigation)

In comparing the maximum differential levels for the two types of slabs, there appears to be little difference in their overall behaviour. Of all the 42 Waffle slabs investigated none met the 1/400 design criteria and only one was better than 1:300. Of all the 42 S-O-G investigated only one met the 1/400 design criteria and only one was better than 1:300.

Even though the 84 slabs quoted here are a biased sample (being slabs that the owner had complained about). The extent of the distortions are unacceptable.

In both types of slabs the average 'Worst case differential slab level' was 36 mm. The largest of these figures was 100 mm for waffles and 70 mm for S-O-G.

Table 16:- Summary of maximum differential levels over the whole slab. (42 Waffle)

≤30 mm	>30 - 50 mm	>50 - 70 mm	>70 - 100 mm
21 No (50%)	14 No (33%)	5 No (20%)	3 No (7%)

Of all the waffle slabs investigated, none met the AS2870 design aim of a maximum differential deflection as a function of span' of ≤1/400 for articulated masonry veneer houses. None were better than 1:250 and the worst case deflection as a function of span slabs averaged 1:115.

Table 17: Summary of maximum differential levels over the whole slab (42 S-O-G).

≤30 mm	>30 – 50 mm	>50 – 70 mm	>70 – 100 mm
22 No (52%)	15 No (36%)	4 No (10%)	NIL

Refer Appendix 1.

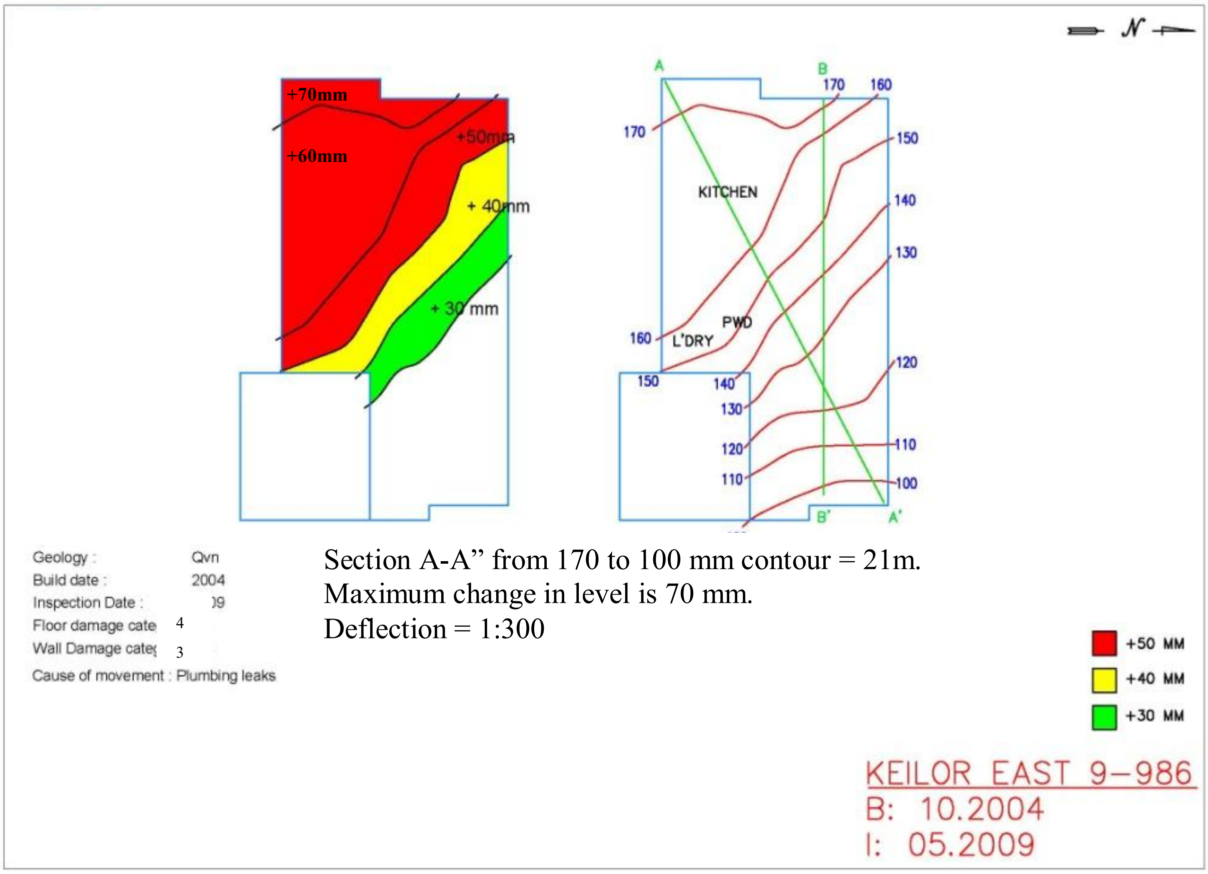

Figure 52: - S-O-G with corner lift - Keilor East, Melbourne.

Comments:

1. This S-O-G has lifted in the rear SW corner due to pipe leaks.
2. Only the front of the slab was unaffected.
3. The coloured area shows the part of the slab that has lifted **>30 mm.**
4. The foundation soil around the coloured area is >>**PL.** (high moisture)
5. The foundation clay is considered abnormally wet near the SW corner.
6. The maximum lift is **70 mm** on the rear wall of the house.
7. The floor damage was category **4** – (High as per AS2870)
8. The wall damage was category **3** – (Moderate)

Refer Appendix 2.

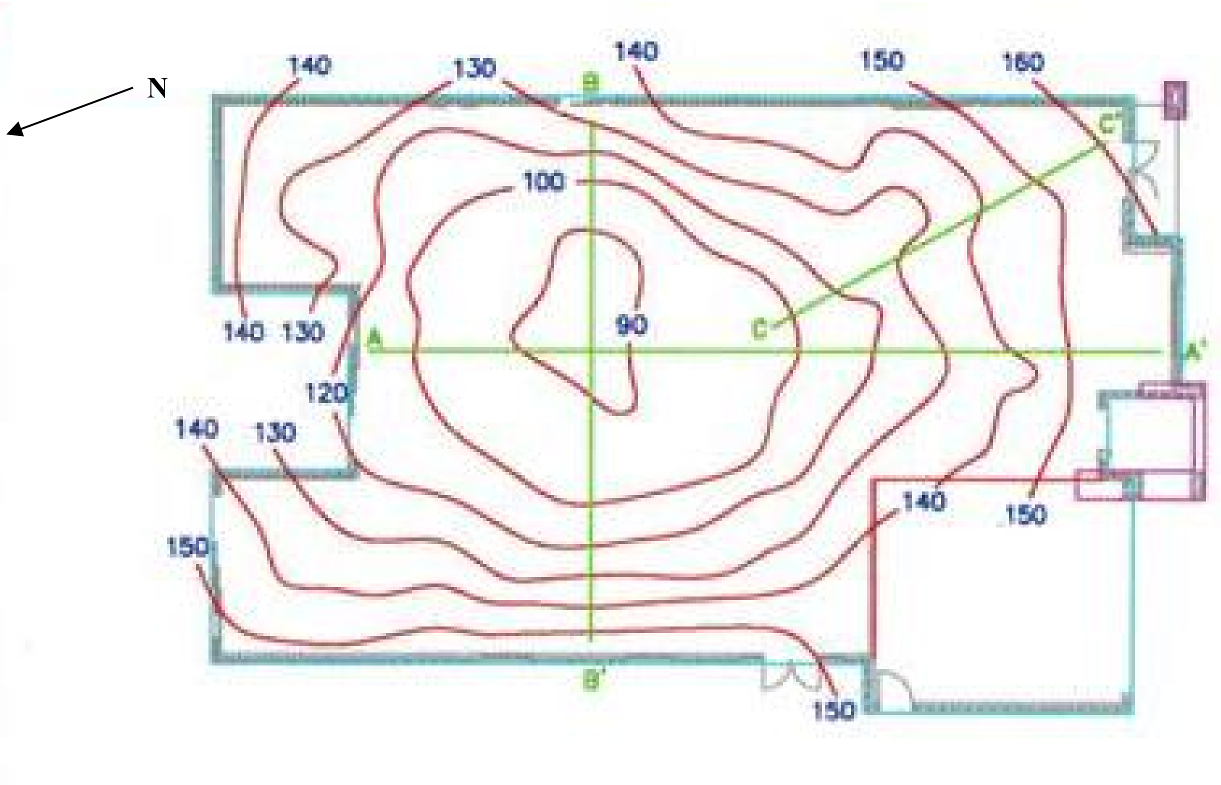

Figure 53: - Waffle slab with perimeter lift - Caroline Springs, Melbourne.

Comments

1. This waffle slab has lifted around the whole perimeter.
2. Only the centre of the slab is unaffected.
3. All the foundation soil around the perimeter is >>**PL**. (high moisture)
5. There was no concrete cover around the perimeter and all surrounds were wet.
6. The cause of the slab lift was found to be several plumbing leaks, most probably due to the cracking of the pipe joints caused by clay swelling or damage during construction.
6. The maximum differential level is **≈70 mm** at the rear South West corner of the house.
7. Both floor and wall damage was category **4** – (High as per AS2870)
   (In most of severely damaged cases more than one prior plaster repair was noted).

Refer Appendix 1.

6.1.3 AS2870 notations for design and performance.

Buildings supported by footing systems design and constructed in accordance with this Standard on a 'normal' site are expected to experience, usually no damage, a low incidence of damage category 1 and an occasional incidence of damage category 2. The design criteria are as follows:

- Maximum slab deflection as a function of span = **1:400.**
- Any slab deflection **>1:150** are undesirable.
- AS2870 does not accept Category **≥3 damage.**

Deemed-to-comply designs are to be used only on 'normal' sites, alternatively the on-site conditions are to be made and maintained 'normal' well prior to construction.

6.2 SUMMARY OF CAUSES OF DAMAGE.

Note that similar causes have been colour coded.

The terminology used by the investigators differed a little therefore, in tables 16 and 17, the summary terms have been grouped and normalised as much as possible for the sake of comparison.

Table 18: Summary of causes of damage in 42 Waffle slabs.

Causes	No of cases	%	Comments on findings
1. Poor drainage	17	40%	Poor preparation and poor drainage at completion.
2. Plumbing leaks	14	33%	Damaged or leaky inflexible pipe joints.
3 Poor landscaping	5	12%	Water allowed to pool near house.
4 Seasonal effects	5	12%	'Normal' seasonal moisture change.
5 Drought effects	2	5%	Soil drying and shrinking.
6 Tree effects	2	5%	Seasonal ground shrinking or swelling.
7 Undetected	3	7%	---
			Two causes were reported for 6 houses.

- Causes 1 and 2 were identified as the builder's responsibility = **73%.**
- Cause 3 was verified as either the owner's responsibility = **12%**.
- Cause 4 and 5 are natural events = **17%**.
- Cause 6 could be the responsibility of a number or parties = **5%.**

Table 19: Summary of causes of damage in 42 S-O-G.

Causes of damage	No of cases	%	Comments on findings.
1. Poor drainage.	22	52%	Poor site preparation poor drainage on completion.
2. Plumbing leaks.	9	27%	Leaking of non-flexible pipe joints.
3. Seasonal effects.	3	7%	Poor landscaping.
4. Poor landscaping.	3	7%	Slab not protected from adjacent water.
5. Drought drying.	3	7%	Soil drying and shrinking.
6. Flood after drought.	2	5%	The flood event were reported by the owner.
7, Tree drying.	2	5%	Responsible by any number of parties.
8. Undetected	4	10%	--
			Two causes were reported for 5 houses.

- Causes 1 and 2 were identified as the builder's responsibility = **79%.**
- Causes 3, 5 and 6 are natural events.= **19%**
- Cause 4 was judged as mostly the owner's responsibility = **7%.**
- Cause 7 was judged to be the responsibility of a number of parties = **5%.**

Most of the research area is near-flat and was originally a eucalypt forest, then farmland for a century or so and is now about half built-on. Some original forest trees remain and the developed areas have new plantings in nature strips and parks.

6.3 CHAPTER 6 CONCLUSIONS

The 84 slabs reported in this thesis were investigated during the builder's maintenance period or in response to an owner's concerns after noting damage (usually after the breaking of the Millennium drought). Most of the slab reported here were constructed during the long 'Millennium' drought on very dry ground.

Chapter 6 Summary:

64% of the Waffles had maximum differential levels ≥30 mm and 24% were ≥50 mm.

45% of the S-O-G had maximum differential levels ≥30 mm and 29% were ≥50 mm.

It is clear that poor drainage and pipe leaks are the greatest cause of slab movement i.e.: 73% for Waffles and 79% for S-O-G and this difference is well within the margin of error or difference of opinions by the investigators. Pipe leaks were 33% for Waffles and 27% for S-O-G possibly due to construction differences or varying skills of plumbing contractors.

These statistics are not conclusive but are a good indication that better drainage would eliminate some of the damage.

The following Chapter 7 explores some concluding remarks that have not been mentioned to this point and presents the new CGM design models for pre and post-construction conditions.

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CHAPTER 7

REVIEW OF PROPOSED NEW DESIGN MODELS.

7.1 PROPOSED DESIGN MODELS.

The models presented in this thesis are to provide more accurate y_s values to cope with a repeat of the chaotic weather conditions that the research area has experienced in the past 30 years. In anticipation of a repetition of these climatic events in the 50 year design life of houses the design surface suction Δu_s has been increased from 1.2pF to 1.5pF in inundation prone land in the warmer climate zones. These conditions are given a climate zone suffix of (a). In this thesis particular attention is given to Climate zones 3(a) and 4(a).

This Δu_s is not new since it was previously proposed by Thorne (1984) and included in AS2870-1986 for a number of areas. However this Δu_s has since been gradually removed from this document. The resultant y_s is not in proportion to the Δu_s in the existing standard model since the I_{ccs} is lower at suctions >4 pF due to the curvilinear relationship described above.

The new Δu_s interval of 3.1–4.6pF has been calculated from field and laboratory testing and the literature review which has indicated a surface moisture range of ≈20% in zone 3a.

The author's conclusion is that the 'Normal' surface suction of 1.2pF does not allow for climatic conditions that are likely during the life of a house built in the research area therefore the higher Δu_s is recommended to allow for a repeat of these climate variations and some other minor risk factors. The need for this change is evidenced by the field, laboratory and slab performance investigations carried out in this area. However the author recommends that similar investigations be carried out in all climate conditions and major soil types in development areas. It is possible that Δu_s may be reduced in more benign climates.

The slab design models presented in this thesis show that during a repeat of the climate conditions experienced in the past 2 decades the Site Classification was inadequate.

The recommended y_s models are a based on experimental findings and laboratory testing. The more extreme suction and moisture values found have most probably been exacerbated by poor building practises, poor landscaping and some owners not fully aware of the restrictions and recommendations in AS2870.

7.2 FIELD MOISTURE RESULTS.

Field moisture results have shown that in 'Normal' conditions (as described in AS28970) in the research varied by ≈ 14% and by ≈20% in the conditions for the past 20 years. Table 20 below has identified conditions which have been Drought, Transitional or Severe Wet.

Table 20: - Moisture sampling dates and climate conditions.

Sampling intervals	Period	Condition
1997 - 2009	'Millennium drought'	Severe drought
2010 - 2011	'El Nina'	Severe wet
2012 - 2014	'Transitional'	Transitional
2014 –mid-2016	'El Nino'	Drought

The results from an extensive sampling for in-situ moisture tests are shown in Appendix 3 and moistures from the CCS tests have been graphed by linking the 3 parameters together (Suctions-Moistures-Shrink) in figures 49 and 50. (Refer Appendix 3)

7.3 NEW CHARACTERISTIC GROUND MOVEMENT MODELS.

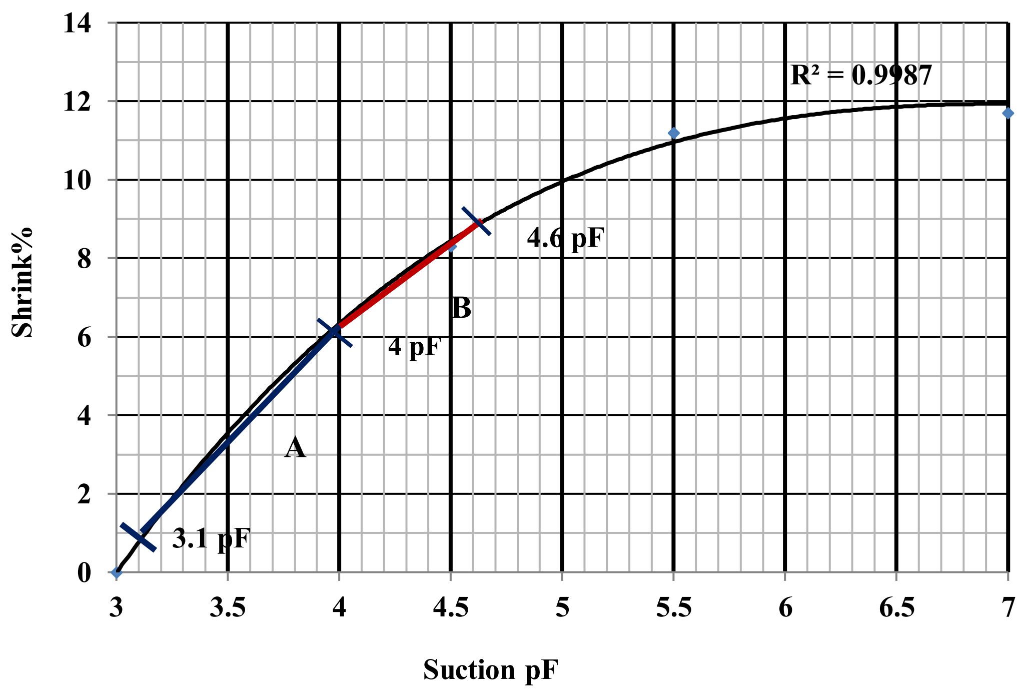


Figure 54: – Typical shrink/suction linear relationships for climate zone 3(a)

The curve in figure 54 can be reconciled to two separate straight lines (A and B). In figures 55 and 56 are divided into 2 triangles. The A sections of the soil profile are represent by Line A in the B sections by line B in figure 54.

The deepest section is simplified into triangle C. These form the basis for the integration of the surficial suctions for climate zones 3(a) and 4(a). The example in figure 54 solves the problem of the curvilinear relationship of 3.1 – 4.6pF. (Climate zone 3(a). The model is divided vertically along the 4pF line to the top of the uncracked C layer and horizontally into 3 layers representing the uncracked profile. Δu of each layer was averaged.

- H_s = 2.3 m
- Layers A1, B1, A2, B2 = 600 thick.
- Layers A3 & B3 = 500 mm thick.
- Layer C = 600 mm.
- Layer C is in the uncracked zone and has an I_{ss} = to the average of layers A3 and B3.
- The effect of the soil confinement factor, $\alpha = {}^{Z}/_{5}$.

7.3.1 Examples of new calculation models of y_s from laboratory results.

1. To allow for the curvilinear relationship of strain/suction the diagram is split vertically into 2 triangles representing the near-linear but different transition zones of 3-4pF and 4-5pF.
2. The soil suction values were integrated with increasing depth.
3. Core samples were taken in each soil layer but at least at 500-600 mm interval.

Braybrook Lot J1

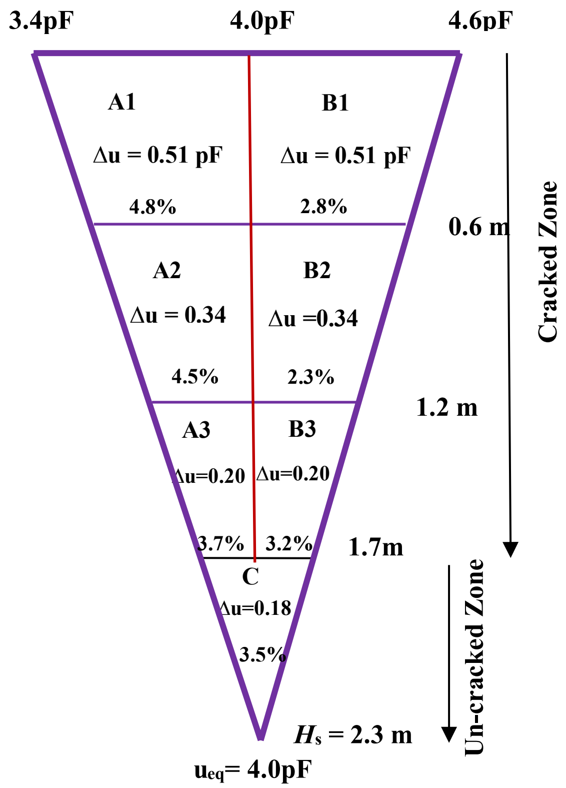


Figure 57: - New model for Braybrook lot J1 for climate zone 3 with Δu_s = 1.2 pF

Table 21: - New y_s model for Braybrook allotment J1, climate zone 3.

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.51	4.0%	1	12.4
A2	600	0.34	4.5%	1	9.2
A3	500	0.20	6.4%	1	6.4
B1	600	0.51	2.8%	1	8.6
B2	600	0.34	2.3%	1	4.7
B3	500	0.20	3.2%	1	3.2
C	600	0.18	. 3.5%	1.6	6.0
	• Quoted to nearest 5 mm			**Total y_s =**	**50mm**

Figure 54 show the shrink/suction curve slope can be simplified into 2 lines. Note that the curve is shallower in the higher suctions that develop in drier climates and steeper in the lower suctions hence the I_{ccs} varies with the suction ranges used. To calculate the y_s in the models presented in this thesis, each I_{ccs} has to be calculated separately for each design condition anticipated or by using a suitable curve equation.

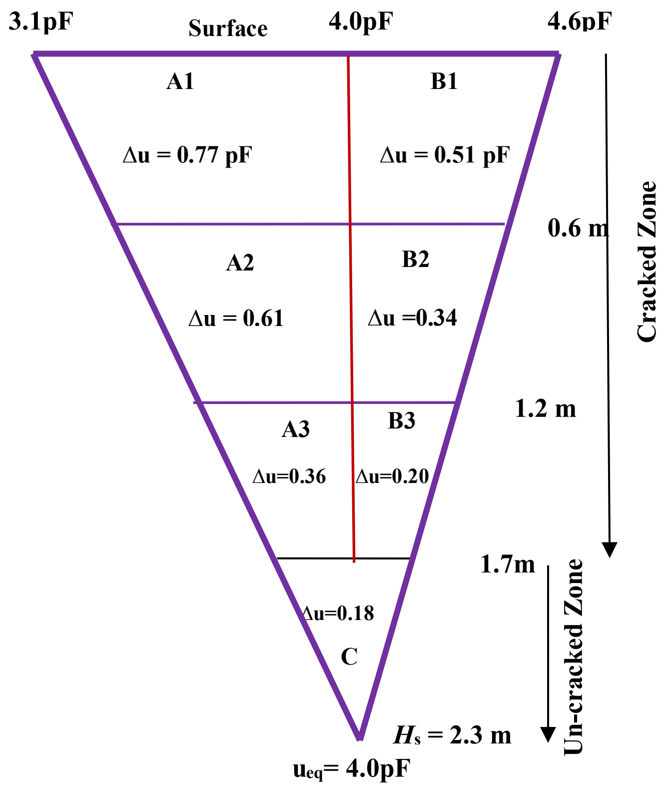


Figure 55: - New y_s model for climate zone 3(a)

Table 22: - New y_s for Point Cook BH 1, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	6.0%	1	27.7
A2	600	0.61	4.9%	1	16.8
A3	500	0.36	5.8%	1	10.4
B1	600	0.51	4.2%	1	12.9
B2	600	0.34	3.3%	1	6.7
B3	500	0.20	3.5%	1	3.5
C	600	0.18	Av. 4.6%	1.6	7.9
• Quoted to nearest 5 mm				**Total y_s = 85 mm**	

Table 23- New y_s for Point Cook BH 2, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	6.3%	1	29.1
A2	600	0.61	5.6%	1	20.5
A3	500	0.36	6.7%	1	12.1
B1	600	0.51	3.7%	1	11.3
B2	600	0.34	3.5%	1	7.1
B3	500	0.20	4.7%	1	4.7
C	600	0.18	Av. 5.7%	1.6	9.8
• Quoted to nearest 5 mm				**Total y_s = 95 mm**	

Table 24: - New y_s model for Tarneit BH 1, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	6.7%	1	31.0
A2	600	0.61	5.4%	1	19.8
A3	500	0.36	8.2%	1	14.8
B1	600	0.51	4.2%	1	12.9
B2	600	0.34	2.8%	1	5.7
B3	500	0.20	4.7%	1	4.7
C	600	0.18	Av. 6.5%	1.6	11.2
• Quoted to nearest 5 mm				**Total y_s = 100 mm**	

Table 25: - New y_s model for Tarneit BH 2, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	4.2%	1	19.4
A2	600	0.61	5.1%	1	18.7
A3	500	0.36	7.0%	1	12.6
B1	600	0.51	3.0%	1	9.2
B2	600	0.34	3.2%	1	6.5
B3	500	0.20	3.3%	1	3.3
C	600	0.18	Av. 5.2%	1.6	9.0
• Quoted to nearest 5 mm				**Total y_s = 80 mm**	

Table 26: - New y_s model for Melton BH 1, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	8.4%	1	38.8
A2	600	0.61	6.9%	1	25.3
A3	500	0.36	6.1%	1	11.0
B1	600	0.51	5.3%	1	16.2
B2	600	0.34	5.0%	1	10.2
B3	500	0.20	3.7%	1	3.7
C	600	0.18	Av. 4.9%	1.6	8.5
• Quoted to nearest 5 mm				**Total y_s = 115 mm**	

Table 27: - New y_s model for Melton BH 2, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	7.0%	1	32.3
A2	600	0.61	4.4%	1	16.1
A3	500	0.36	5.9%	1	10.6
B1	600	0.51	3.6%	1	11.0
B2	600	0.34	3.4%	1	6.9
B3	500	0.20	3.7%	1	3.7
C	600	0.18	Av. 4.8%	1.6	8.3
• Quoted to nearest 5 mm				**Total y_s = 90 mm**	

Table 28: - New y_s model for Melton South. BH 1, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	5.9%	1	27.3
A2	600	0.61	7.8%	1	28.5
A3	500	0.36	5.8%	1	10.4
B1	600	0.51	3.0%	1	9.2
B2	600	0.34	4.0%	1	8.2
B3	500	0.20	3.2%	1	3.2
C	600	0.18	Av. 4.5%	1.6	7.8
• Quoted to nearest 5 mm				**Total y_s = 90 mm**	

Table 29 - New y_s model for Melton South BH 2, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	6.0%	1	27.7
A2	600	0.61	3.8%	1	13.9
A3	500	0.36	5.1%	1	9.2
B1	600	0.51	3.7%	1	11.3
B2	600	0.34	3.3%	1	7.8
B3	500	0.20	3.5%	1	3.5
C	600	0.18	Av. 4.6%	1.6	7.9
• Quoted to nearest 5 mm				**Total y_s = 95 mm**	

Table 30: - New y_s model for Braybrook BH J1, climate zone 3(a)

	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	4.6%	1	21.3
A2	600	0.61	5.4%	1	19.8
A3	500	0.36	6.1%	1	11.0
B1	600	0.51	2.8%	1	8.6
B2	600	0.34	2.3%	1	4.7
B3	500	0.20	3.2%	1	3.2
C	600	0.18	Av. 4.7%	1.6	8.1
• Quoted to nearest 5 mm				Total y_s = 75 mm	

Table 31: - New y_s model for Braybrook J2, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	6.1%	1	28.2
A2	600	0.61	7.8%	1	28.5
A3	500	0.36	8.4%	1	15.1
B1	600	0.51	2.8%	1	8.6
B2	600	0.34	3.8%	1	7.8
B3	500	0.20	5.0%	1	5.0
C	600	0.18	Av. 6.7%	1.6	11.6
• Quoted to nearest 5 mm				Total y_s = 105 mm	

Table 32: - New y_s model for Plumpton BH 1, climate zone 3(a)

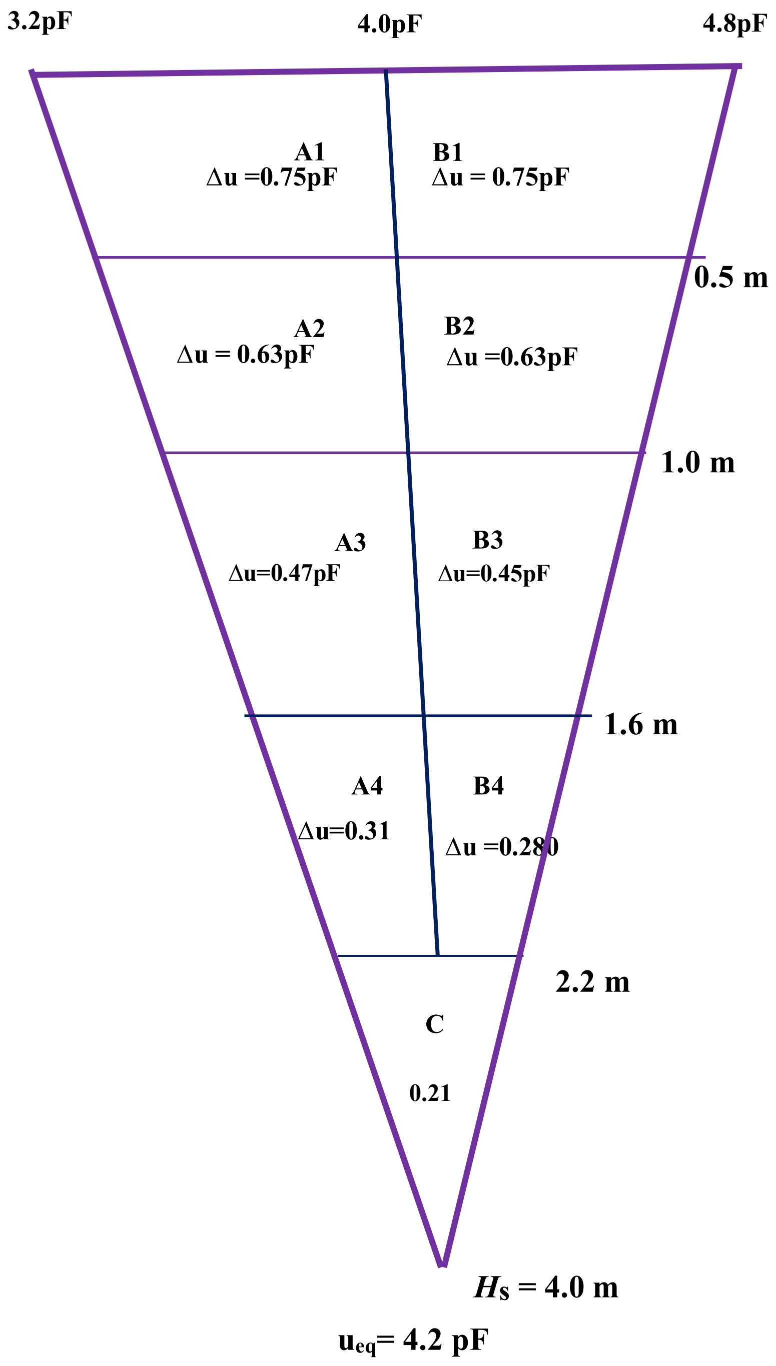
Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	4.5%	1	20.8
A2	600	0.61	5.7%	1	20.9
A3	500	0.36	6.4%	1	11.5
B1	600	0.51	2.5%	1	7.7
B2	600	0.34	3.2%	1	6.5
B3	500	0.20	5.5%	1	4.5
C	600	0.18	Av. 4.9%	1.6	9.5
• Quoted to nearest 5 mm				Total y_s = 80 mm	

Table 33: - New y_s model for Plumpton BH 2, climate zone 3(a)

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.77	6.6%	1	30.5
A2	600	0.61	7.4%	1	27.1
A3	500	0.36	7.9%	1	14.2
B1	600	0.51	4.3%	1	13.2
B2	600	0.34	4.2%	1	8.6
B3	500	0.20	4.3%	1	4.3
C	600	0.18	Av. 6.1%	1.6	10.5
• Quoted to nearest 5 mm				Total y_s = 110 mm	

The I_{ccs} of the Pt Cook bore hole 1 have been used in figure 56 show the y_s for a similar site in climate zone 4(a). The model was extended to H_s = 4 metre and the u_{eq} to 4.2pF.

The resultant y_s in climate zone (4a) is 118 mm compared with 85 mm in climate zone 3(a).



A1, 0.75 x 5.9% x 500 x 1 = 22.1

B1, 0.75 x 4.6% x 500 x 1 = 17.3

A2, 0.63 x 4.9% x 500 x 1 = 15.4

B2, 0.63 x 3.3% x 500 x 1 = 10.4

A3, 0.47 x 5.7% x 600 x 1 = 16.0

B3, 0.45 x 3.3% x 600 x 1 = 8.9

A4, 0.31 x 5.7% x 600 x 1 = 10.6

B4, 0.28 x 3.5% x 600 x 1 = 5.9

C 0.21 x 4.6% x 800 x 1.6 = 12.4

Total y_s (to nearest 5 mm) = 120mm

Figure 56: - New y_s model for Climate zone 4(a).

7.3.2 Summary of y_s and y_m. as per the new model.

Table 21-32 show the I_{ccs} and y_s calculated from 36 undisturbed samples collected in 6 allotments and 12 bore holes. Table 33 summarises the y_s and y_m from these results.

- The y_s were calculated using the new model recommended here and the $I_{ccs} \equiv (I_{ps})$ values averaged from the testing reported in Appendix 5.
- Most slabs built up to 2012 were designed to a maximum y_s of 70 mm per AS2870.

Table 34: - Summary of y_s and y_m for new model.

Location	Zone 3a $\Delta u_s = 1.5$ pF	Δy_s at each site	$y_m = 0.7y_s$ (Mitchell 1996)	y_m variation
Point Cook BH 1	85 mm		60 mm	
Point Cook BH 2	95 mm	10 mm	67 mm	7 mm
Tarneit BH 1	100 mm		70 mm	
Tarneit BH 2	80 mm	20 mm	56 mm	14 mm
Melton BH 1	115 mm		80 mm	
Melton BH2	90 mm	25 mm	63 mm	17 mm
Melton Sth BH 1	95 mm		67 mm	
Melton Sth BH 2	85 mm	10 mm	60 mm	7 mm
Braybrook BH J1	80 mm		56 mm	
Braybrook BH J2	105 mm	25 mm	74 mm	18 mm
Plumpton BH 1	80 mm		56 mm	
Plumpton BH 2	110 mm	30 mm	77 mm	21 mm
Indicative range	80 – 115 mm		56 – 80 mm	

- The largest variations of the average y_s in a single allotment was 30 mm at Plumpton 25 mm at Braybrook and Melton and .20 mm at Tarneit.
- The average $y_s = 93$ mm and average $y_m = 65$ mm.
- The y_s gives some indication of the variability of soil types on each allotment and overall.
- The y_m values varied from 56 to 80 mm.
- At the time of construction of these houses 'H' classification was used which allowed a maximum y_s of 70 mm and a design y_m of 49 mm.
- The results in the summary in table 33 show that all the sites investigated require stiffer slabs and/or better drainage.
- The y_s variation suggests that all the sites tested had a variation greater than one classification category.
- It is estimated that in basaltic clays in climate zone 3 the range of classification = H2 – E and in climate zone 3(a) = ≥ E.

Tables 34 and 35 indicate that with proper drainage and not subject to inundation or tree-effect conditions these allotments would have a 'H2' Classification.

Braybrook Lot J2

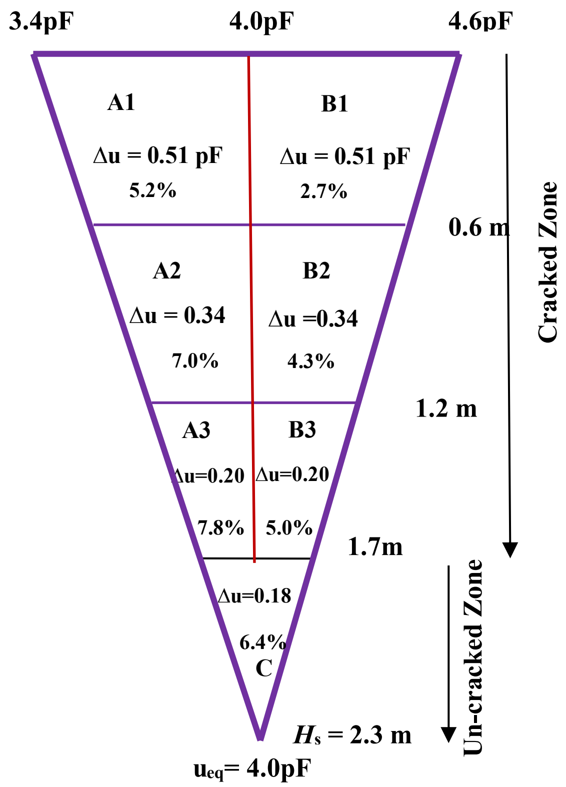


Figure 57: - New model for Climate zone 3

Comparing the results from Lot J1 and J2 demonstrates the soil index variation possible over a short distance even in sites with very similar geological origins.

Table 35: New y_s model for Braybrook for the same profile as BHJ2, climate zone 3.

Soil layer	Layer depth (mm)	Average Δu	I_{ss}	α	Δy_s^n
A1	600	0.51	5.2%	1	15.9
A2	600	0.34	7.0%	1	14.3
A3	500	0.20	7.8%	1	7.8
B1	600	0.51	2.7%	1	8.3
B2	600	0.34	4.3%	1	8.8
B3	500	0.20	5.0%	1	5.0
C	600	0.18	. 6.4%	1.6	11.1
• Quoted to nearest 5 mm				**Total y_s = 70 mm**	

7.4 CAUSES OF DAMAGE DUE TO SITE CONDITIONS

7.4.1 General.

The results from this research show that the 'Normal' conditions can be exceeded by severe climate conditions (as recently experienced), poor construction practises, poor site maintenance or changes to the site conditions. Unless owners are fully informed they may not be aware of the restrictions in the site classification and design methods in AS2870 and hence expect a better performance of their house than can be delivered under this Standard.

This research has found that the unsatisfactory performance of house slabs built in the research period (2005-2014) has been caused by a confluence of:

- Recent extreme weather.
- Water regulations during the drought.
- Building boom.
- Building practices.
- Highly expansive foundation soils
- Engineering designs.

The local economy is very sensitive to housing costs therefore any major changes to AS2870 need very careful considerations and home owners should be made aware of the increased risks created by climate change.

7.4.2 Recent extreme weather.

The recent extreme weather has occurred twice in the last 100 years and due to the expected climate change, which is likely to occur more often and be more severe. Other droughts followed by heavy rain have occurred at roughly 10 year interval. These have been less severe, but in the future, (50 years design life of houses), they are likely to be similar or more severe than the recent extreme weather period. If so, designing and building will be more onerous to the engineer and builder unless designs and practises are improved to suit the conditions.

The author's conclusion is that the 'Normal' surface suction change of 1.2 pF has not allowed for the recent extreme climate conditions in this area and is unlikely to allow for climatic conditions during the life of a house. However it is likely that the 1.2 pF value is sufficient in more benign climates provided the house sites are well drained. If the conditions experienced in the research period are repeated in the expected design life of the houses (50 years as per AS2870) this conclusion should be re-examined.

The consensus from climate scientists is that droughts may be more severe and occur more often in the next 50 years. It is hoped however that effect of the sudden downpours can be reduced by better site drainage.

7.4.3 Water regulations during ‘Millennium’ drought.

During the last drought home owners were generally not permitted to water their gardens other than by manual methods. The only permit to use water on gardens was for a maximum of 6 weeks to water only newly sown grass. This applied to many houses in the research area and began the ‘slab lift’ problem even before the rains came.

7.4.4 Building boom.

Due to an increase in immigration and a sudden high demand for new housing, particularly in the Western and Northern suburbs of Melbourne and the lack of skilled tradesmen caught many builders short of skilled staff and experienced supervisors.

The research area is mostly a flat basaltic plain which is difficult to drain. Many houses were built without adequate drainage and the increased use of waffle slabs (which are built on levelled land) led to poorly drained allotments extremely susceptible to ground heave. Some of the problems began during construction and continued after occupation.

7.4.5 Highly expansive foundation soils.

The lack of experience in building in these soil types and the length of the drought and flooding period caught some consultants and most builders unawares. Most of the larger builders had been building in much less troublesome soils for many years in the Eastern and Southern suburbs. Most of their consultants were also less aware of the severity of the issues with these soils. The clays in the research area are mainly Calcium and Sodium Smectites which have a high shrink/swell potential and Liquid Limits in the range of 70%-120%.

7.4.6 Engineering designs for the 50 year life of house.

The slab designs used during the drought were ‘H’ type which AS2870 recommends for a maximum y_s of 70 mm. Later in the drought some practitioners began to stiffen their slabs in recognition of the very dry conditions.

The author's conclusion is that the "Normal" surface suction of 1.2pF does not allow for all climatic conditions that are likely during the life of a house. This thesis suggests a minimum Δu = 1.5pF would allow for some climatic changes and other risk factors in this part of Melbourne. However the need for better site drainage is still required.

7.4.7 Home owner's responsibilities per AS2870.

Some of the performance restrictions in AS2870 place certain responsibilities on the owner; such as:

- Taking any action which would change the site classification.
- Failure to maintain site drainage which would change the classification.
- Failure to repair plumbing leaks.
- Loss, planting or allowing trees or dense vegetation to grow near the building.

Not following these restrictions were some of the contributing causes of damage.

7.4.8 A new approach to slab design for greater soil suction variation.

Adopting table 15 and a Δu_s = 1.5 pF for Climate zone 3(a) would reduce slab performance problems for the near future. Implementing these designs gives the engineer more design opportunities to cope with the relevant site conditions and the expectations of the owner.

If the AS2870 restrictions and recommendations were followed, a design Δu_s of 1.2pF would suffice in climate zone 1, 2 and 3. However in drier but inundation-prone zones a minimum of design Δu_s of 1.5pF is required to deal with recent climate conditions.

However the home owners should be made aware that even these higher design suctions are not adequate if the respective responsibilities are not strictly followed by the builders and home owners. A drier atmosphere can 'carry' more water therefore all parties should understand that a future drier climate will cause greater soil shrink and the heavier storms that follow will cause greater footing 'lift'.

However, Walsh and Cameron (1997) argue that:

"From the point of view of the community as a whole, it is optimal if the cost of failures is balanced against cost of excessive construction and design costs. Footings are designed to regulations and standards and it is all too easy to aim for unrealistic performance expectations that are to the detriment of home owners collectively".

The author expects that the outcome of this research will provide new slab design models for a greater variety of conditions than outlined in AS2870, however to do so regular similar investigations to those presented here are required for a constant the up-dating of AS2870 and practitioner's knowledge.

7.5 CHAPTER 7 CONCLUSIONS.

In this chapter Characteristic Ground Movement has been discussed in detail and *y*s have been calculated using a new model for Climate Zone 3 and 3(a) and has been interpolated for climate zone 3(a).

Two models have been developed similarly to the triangular model in AS2870 with modifications to deal with the curvilinear shrink/suction issue and the recent drought and inundated land conditions.

The effect of these changes is that the *y*s in the inundated areas requires a higher 'Classification'.

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CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 OUTCOMES.

The author's conclusion is that the 'Normal' Δu_s 1.2pF has not allowed for the recent extreme climate conditions in this area and is unlikely to allow for climatic conditions that are likely during the life of a house. However this value may be sufficient in more benign climates provided the house sites are well drained. If the conditions experienced during the research period are repeated in the expected design life of the houses (50 years as per AS2870) this conclusion should be re-examined.

Designing for a repeat of the climate conditions that were experienced recently would greatly increase the cost of houses and new home owners can least afford to litigate or repair the damage. The consensus from climate scientists is that droughts may be more severe, and occur more often in the next 50 years. It is hoped however that effect of the sudden downpours can be reduced by better site drainage by the builder and owner by a better adherence to AS32870.

The local economy is very sensitive to housing costs therefore any major changes to this standard needs very careful considerations; on the other hand the industry should be constantly aware of the increased risks created by climate change. The 'Normal' site conditions can be exceeded by severe climate conditions, poor construction practises and poor maintenance or changes to the site. Unless owners are fully informed they may not be aware of the restrictions in the site classification and design methods in AS2870 and hence expect a better performance of their house than can be delivered. Owners may also plant or allow unsuitably 'active' trees to be planted, in so doing they do not consider, any detrimental changes that may occur.

8.2 IMPORTANCE OF INITIAL MOISTURE IN TESTING.

The curvilinear relationship in measuring shrinking and swelling properties of clays makes it difficult to measure soil index properties especially in the drier climates. Where the soil index is to be measured in the linear part of the curve, (3-4pF) the index can be considered constant however in soil profiles where the suction is >4 pF suction measurements are necessary.

A modified and 'conditioned' shrink test has been proposed in this thesis to overcome 2 issues.

1. Narrowing the test to one process i.e. shrinkage and not attempting to join a swell path with a shrink path.
2. Conditioning the initial suction of sample to 3.0-3.5pF.

In table 36, (P. 48) the variations in the I_{ss} were calculated by using the shrink/swell test results from undisturbed soil samples (After Karunarthne 2016). These samples were 50mm in diameter and sampled to a depth of 2.3 metre within a 2^2 metre area in one of the allotments for his PhD research in Braybrook and within a few metre of Braybrook bore hole, J1. (Appendix 5)

Table 36: - y_s calculated from different I_{ss} values and initial moistures.

Depth (m)	ΔZ (mm)	Av. Δu for leach layer	α:	Date 8/8/2013 Wet	Date 8/8/2013 Moderate	Date 8/8/2013 Dry	y_s (mm)		
							Wet	Moderate	Dry
0-1.0	1,000	1.026	1	6.46%	5.51%	4.19%	66.3	56.5	43.0
1.0-1.5	500	0.591	1	6.46%	5.51%	4.19%	19.1	16.3	12.4
1.5-1.725	225	0.378	1	6.72%	5.65%	5.3%	5.7	4.8	4.5
1.725-2.3	575	0.200	1.62	6.72%	5.65%	5.3%	12.5	10.5	9.9
Refer table 2 as an example of the variation of I_{ss} when testing soils in different soil moisture conditions.						y_s	103.6	88.1	69.7
						Site class	E	E	H2

8.3 THE PARAMETERS FOR NEW MODELS.

The author has proposed parameters for a new model by considering 6 data sources:

1. Researched papers as quoted for H_s, Δu_s, α, u_{eq} and TMI values.
2. 267 moisture results (Δu_s) from testing during the research period (Brown et al).
   (Moistures recorded only from sites that qualified as normal)
3. Investigation of 85 houses as part of this thesis.
   (Recording degree of foundation soil condition, degree of damage and causes)
4. 36 Conditioned Core Shrinkage (CCS) tests from research area.
   (Determining soil indices for each sample.
5. 36 Soil-Water/Suction Characteristic Curves. (SWCC)
   (Determining water/suction relationship for each sample)
6. Grouped (SWCC) from the 6 suburbs tested.
   (Determining a general water/suction curve for the area.

8.4 CHARACTERISATION MODEL FOR A MORE CHAOTIC CLIMATE.

A simple change to AS2870 Table No 2.4 drawing attention to a 1.5pF Δu for flat inundation-prone land in the western and northern suburbs and 1.2pF for well-drained sloping land for the remainder of this area could reduce slab performance problems for the near future. Implementing these designs gives the engineer more design opportunities to cope with the relevant site conditions and the expectations of the owner.

Almost all commercial products are available with a choice of design and performance. There is no reason why this should not also apply to houses. The potential home owner should be made aware that AS2870 deemed-to-comply slab designs have very restrictive conditions which they may not want to accept. In the last 20 years the deemed-to-comply AS2870 slab designs did not suit many of the site conditions and should have been designed for a 'P' (Problem) classification requiring the slab to be engineer-designed. In these conditions Section 4 of the Standard ('Design by Engineering Principles') is not of much help because the resultant designs are similar to the deemed-to-comply; the only advantage being that the design is signed by a qualified engineer.

To determine the y_s using the models proposed, each I_{ccs} is to be calculated separately for each design condition anticipated (or preferred). As stated by a number of researchers including Fredlund et al the part of the curve which is linear is at suctions ≈3–4 pF; however over shorter suction intervals (such as Line A and B) a linear relationship is also reasonable.

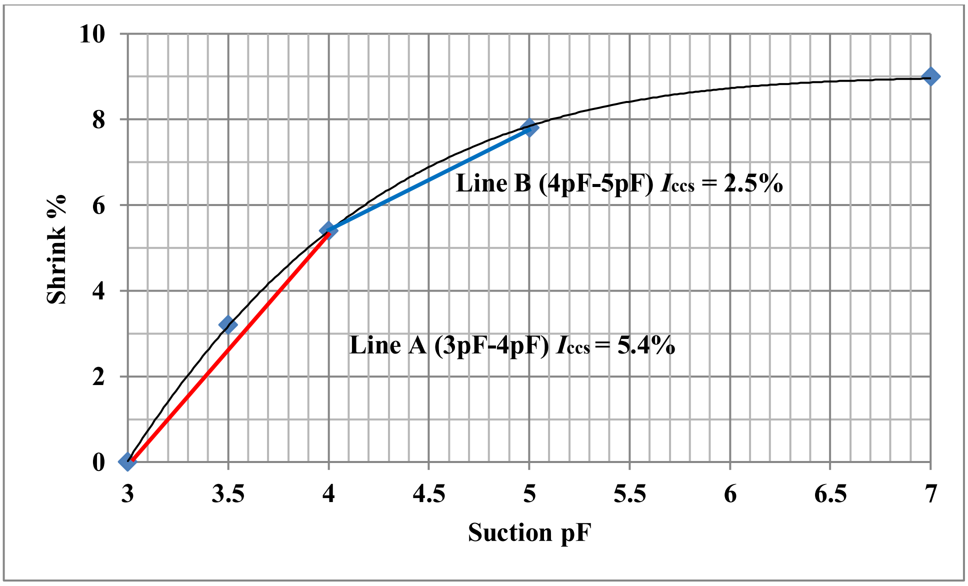

Figure 58: - Typical changes in I_{ccs} using polynomial order 3 curve.

Figure 59 shows how the Shrink/suction relationship varies from greatly over the drier ranges of suction. To calculate the I_{ps} and I_{pt} the two lines can be used to approximate most conditions however a more accurate method is to use the actual Δu_s separately or in combination. For the new model outlined here 3.1-4.6pF is recommended. This interval is chosen to cope with a repeat of the climatic conditions that occurred in the test area in the past 30 years. If poor site drainage and pipe leaks could be totally eliminated a $\Delta u = \leq 1.2$pF would suffice in the more benign climates. However it would be difficult for some absent home owners to maintain the normal conditions required by AS2870. In more chaotic and drying climates the risk of damage increases therefore it is suggested that home owners and builder new and more conservative design with fewer restrictions.

Concerning these limitations, Walsh P. and Cameron D. (1997) argue that:

"From the point of view of the community as a whole, it is optimal if the cost of failures is balanced against cost of excessive construction and design costs. Footings are designed to regulations and standards and it is all too easy to aim for unrealistic performance expectations that are to the detriment of home owners collectively".

It is expected that the outcome of this and subsequent research will provide new slab design models for a greater variety of conditions than outlined in AS2870.

The practicality of testing and using new parameters and the resulting designs will need to be applied to field conditions and the extra (if any) building costs considered.

New field and laboratory testing methods may have to be designed and their results tested on constructed slabs with realistic environmental conditions in mind.

Other recommendations are that Australian Standards susceptible to the effects of climate change are reviewed more often and a risk assessments made regularly in every state based on scientific research.

8.5 AIMS ACHIEVED

8.5.1 Depth of soil suction variation (H_s).

AS2870 based the H_s on TMI ranges as shown in figures 19 and 20 and tables 3, 4 and 5 in chapter 2. The climate zone for the research area is considered temperate but prone to occasional inundation. In AS2870 the TMI range for this area is -5 to -15 and similar in range to Dry–sub-humid in USA according to Peterson et al. figure 28.

The 'active' depth (H_s) for climate zone 3 quoted by the following researchers using TMI values varied as follows:

Table 37: - Data source for new model (H_s) for climate zone 3.

Research quoted	Active depth (H_s)
Fityus et al. (1998)	2.3 - 2.7 m
Mitchell (2008)	2.3 – 3.0 m
AS2870 (2011)	2.3 m
Leao & Osman-Schlegel (2013)	3.0 m
Buxton et al. (2016)	2.3 – 3.0 m

8.5.2 Equilibrium suction variations in different climate zones. (u_{eq})

Table 38: - Data source for u_{eq} in different climate zones.

Climate zone	Mitchell u_{eq} (pF)	Russam and Coleman u_{eq} (pF)	Author's interpolation of u_{eq} from research data
1	3.9	2.9	3.7 pF
2	3.9	3.3	3.9 pF
3	4.0	3.7	4.0 pF
3(a)	4.0	---	4.0 pF
4	4.1	4.1	4.2 pF
4(a)	4.1	---	4.2 pF

8.5.3 Surface suctions (wet to dry) in different climate zones.

Table 39: - Data source for Δu_s in various climate zones.

Climate zone	AS2870 (Δu_s)	Mitchell (2008)	Interpolation from results.
1 –Alpine & Wet coastal	1.2pF	3.7 - 4.9pF	3.2 – 4.2pF
2 – Wet Temperate	1.2pF	3.6 - 4.8pF	3.3 – 4.5pF
3 – Temperate	1.2pF	3.6 – 4.8pF	3.4 – 4.6pF
3(a) – Temperate, inundation prone	-----	-----	3.1 – 4.6pF
4 – Dry temperate	1.2 pF	3.5 – 4.7pF	3.5 – 4.7pF
4(a) - Dry temperate, inundation prone	-----	-----	3.2 – 4.7pF
5 – Semi-arid	1.2 pF	3.55-4.75pF	3.6 – 5.1pF
5(a) – Semi-arid, inundation prone.	-----	-----	3.3 - 5.1pF

In the proposed new model the author has used the following parameters for climate zone 3(a):

- H_s = 2.3m.
- Δu_s = 3.1-4.6pF = 1.5pF
- u_{eq} = 4.0pF

8.5.4 CCS test results as a predictor of y_s.

This test was found to be simple, economical and efficient predictor of ground movement where the net soil stress does not vary. The sample used is 'undisturbed' thus eliminating the issue of hysteresis and adding more consistency to the test. No corrections are necessary and the test of highly expansive clays can be completed in 5-8 days. A recent modification of this test is to take advantage of some in-situ suction conditions. The 'conditioning' of the test is not necessary if the sample arrives at the laboratory at a suction of 3-3.5pF. This can be established by simply testing the two ends of the shrink sample in the psychrometer. If it is wetter or drier than the 3-3.5pF the length of the conditioning process can be better estimated and the drying or wetting process of the main test sample begun. The suction and shrink is measured contemporaneously at each drying stage and the I_{ccs} calculation is quite simple once the shrink/suction curve is drawn. Microsoft, polynomial order 3 or 4 can be used to draw a line of best fit.

The y_s in climate zones which are inundation prone is greater than in 'Normal' conditions and the additional ground movement will occur due to the lower suction values during inundation. In the area tested (climate zone 3(a) this extra ground moisture after the breaking of the Millennium drought was found to be approximately 10% higher than that measured during Normal periods. Clearly some of the extra moisture was due to poor site drainage contrary to the requirements in AS2870; however the natural inundation conditions were also a significant contributor to the higher site moistures and ground movement. Also, naturally higher TMI conditions caused drier site moistures during construction and increased the slab lift in the wet period that followed.

The y_s used by local engineers during the Millennium drought was mostly 40-70 mm ('H' classification), The geological method for classification in AS2870 suggested a classification of 'H-E' which is based on a y_s of 40-70 mm and 70-100 mm respectively The authors field experience is that 'E' classification was very rarely used.

8.5.4 Examples of 'H' classification y_s with new model prediction of y_s.

The calculated y_s from of the laboratory results derived from 36 CCS tests (6 per allotment) were as follows:

Table 40: - Example of y_s and y_m using new model (3a).

Suburb	Max. 'H' (prior 2011) classification y_s	Calculated y_s in new Zone 3(a) model.	$y_m = 0.7\ y_s$ (Mitchell)
Pt Cook	70 mm	Av. = 90 mm	63 mm
Tarneit	70 mm	Av. = 100 mm	70 mm
Melton	70 mm	Av. = 113 mm	79 mm
Melton South	70 mm	Av. = 95 mm	67 mm
Braybrook	70 mm	Av. = 105 mm	74 mm
Plumpton	70 mm	Av. = 108 mm	76 mm

<u>The comparisons on Table 40 indicates that the allotment tested were 'H2' sites in 'normal' conditions but 'E' sites due to inundation.</u>

It should be noted that the y_m is not equal to the slab distortion it is merely the differential soil heave. In the case of slab perimeter heave the soil is mostly in contact with the slab however if there is severe centre heave the slab edge may lift and lose contact with the foundation soil in some places. In extremely dry or wet conditions the house corners experience the greatest movement. During the research period both types of slab distortion took place. During the Millennium drought the edges of the slabs settled due go clay drying creating a part or fully convex shape. This caused mainly perimeter brick wall cracking diagonal or stepped corner cracking. Exterior wall cracks were commonly ≥category 3 (moderate) as per AS2870 Appendix C.

The average lift for all the Waffle slabs was 40 mm in Appendix 1 and 35mm for the S-O-G in Appendix 2. However, due to the sample bias, it is difficult to conclude that the S-O-G are performing better than Waffle slabs.

8.5.5 50 year design life of houses in new climate.

AS2870 states that the footing designs are for an expected 50 year life of houses. With changing climate this expectation would need more regular up-grading of the Australian Construction Standards. Atmospheric scientists are advising that climate change will particularly affect south western, Western Australia and south Eastern Australia.

These changes will create more extreme climates and more extreme soil moisture conditions. The author therefore recommends:

- More regular investigations of soil site conditions.
- More regular revisions of Australian Building Standards.
- Improving the construction standards.
- Better communications with all parts of the industry, including owners.
- A better inspection regime in all stages of construction.

8.5.6 Construction practises which contribute to excessive foundation movement.

A list of such practises would be exhaustive but most are affected by:

(a) A more chaotic climate.

(b) Lack of attention to site soil drainage.

In the past 3 decades AS2870 has been held back by other regulatory bodies; the practical removal of the inspection system and considerable reduction of building site area. However, the more serious problems are the changing moisture in highly expansive clays. Greater consideration should be given to the control of soil water rather than more concrete and steel. This also applies to reducing cost of construction and protection of trees and houses.

Combination of tables 18 and 19 showed that poor site drainage accounted for 55% of the identified causes of damage in both slab types, Pipe leaks 26% and other excess water causes averaged 20%.

In 2011 the greatest slab movement was edge and corner lift. Caused by approximately 10% increase in the wettest moisture in 'Normal' conditions. This is equivalent to approximately 0.4pF and an additional soil mound movement of 25-35 mm. (Refer figure 49 & 50)

8.6 RECOMMENDED FURTHER RESEARCH.

8.6.1 Further research into soil parameters

The research results were very valuable in testing the highly expansive basaltic clays, however, it is obvious that different weathering, soil types, clay mixtures, fabric and climate conditions are all important in producing their Characteristic Ground Movement. Surface suction parameters and soil indices recommended here are probably within the accuracy required for the site classification terminology used in AS2870, however the TMI and the depth of *Hs* relationship needs more specific field and laboratory investigations.

To design footings that can cope with the recent climate conditions and more severe expected conditions the 'deemed-to-comply' footings, either require an expanded classification system, or a stricter design method by Engineering Principles. More field and laboratory testing is also required to better represent the swelling and shrinking and the shrink/suction/moisture relationship of various soils. To achieve these solutions more field and laboratory research is required.

8.6.2 Further research into climatic effects and drainage pre-construction.

Climate and atmospheric information and models are being continually improved as data accumulates. However each International Panel on Climate Change (I.P.C.C) report strengthens the likelihood of future climates in Victoria being more chaotic with increasing temperature, humidity and energy in the atmosphere. With respect to engineering shallow footings and roads, more attention should be given to researching the effects of these changes.

A simple test in preparation for house construction in highly expansive clays are soil moisture tests with reference to suction, such as in figures 49 and 50. Such a test should be carried out immediately prior to construction and could be combined with other useful geotechnical and site drainage observations in preparation to pouring concrete. BoM publishes soil moisture information at very regular intervals which can also reflect building conditions.

8.6.3 Further research into shrink/swell of highly expansive clays.

The popularisation of easy-to-use and more accurate psychrometers has made a great difference to soil index testing. The development of one instrument that measures moisture, suction and strain is not far off. Consistent and comparable results are most important in laboratories and although the tests should reflect the field conditions they can be rarely be achieved accurately, hence modelling is still in its infancy. In this research it became obvious that even in similar geological settings the soil indices varied considerably. This variation was caused by a variety of chemical and non-expansive soil 'inclusions' which are impossible to predict.

8.7 CONCLUDING REMARKS

The research in this thesis attempted to combine the data gathered from a number of sources and personal work however it was difficult to connect all the results to any particular house mainly due to privacy issues. Although some valuable conclusions have been drawn they are particularly relevant to Smectite clays of basaltic origin.

The characterisation parameters have been well studied individually but have been difficult to link together to form accurate models. This needs more attention in future research.

Melbourne has a number of clay groups which could also be examined with similar test methods and the data linked together in a co-ordinated way. There is a wide scope for similar research on other soil types however this thesis has concentrated on one of the most reactive clays occupying a large area.

The basaltic plains in Southern Australia are among some of the largest in the world and are being populated by houses which have performed less well than expected. All the authorities, companies and practitioners that are responsible for the success of the building industry should contribute to further research for the benefit of the consumer. The state and federal authorities should oversee the use of better products and the inspection of best practices.

Dominic Lopes

Swinburne University of Technology, Melbourne Australia.

31/7/2017

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APPENDICES

APPENDIX 1

SLAB DAMAGE CATEGORY NOTATIONS & SLAB CONTOURS (42 Waffle Slabs)

Notes: Classification of damage categories of concrete floors and walls is used as a reasonable performance expectation. The wall damage categories are not quoted since in many cases the walls had already been repaired at least once. AS 2870 considers damage category 2 as 'slight', 3 moderate and 4 severe and an overall deviation of floor slope in excess of 1:150 is considered undesirable and the maximum design slope is 1:400.

Houses supported by footing systems designed and constructed in accordance with this standard on a 'Normal' site that are not subject to 'abnormal' moisture conditions; and maintained such as the original site classification remains valid **are expected to experience usually no damage, a low incidence of damage category 1 and an occasional incidence of category 2.**

Each contour plan notes the Geology, built date, test date (English style), floor damage category, assessed cause of movement and suburb; however, due to privacy issues, the street and house numbers have been omitted. The full address is recorded in the investigation files. All of the houses were built during the Millennium drought; 5 were investigated during this drought and 37 after the breaking of the drought. Of the 42 houses only 13 had a differential slab distortions ≤30 mm. The investigations were part of the scheduled maintenance by large builders and is considered as an example of the response by the builders to the concerns of the home owners during this time.

Location	Worst-case slab differential levels (mm)	Worst-case deflection as a function of 3 m span. (AS 2870 design 1/400)	Floor damage category per AS2870	Comments	Cause
Bacchus Marsh (1)	**30**	**1:109**	**3**	**Front of house lifted.**	**Poor front garden drainage**
Bacchus Marsh (2)	**20**	**1:100**	**1**	**Minor edge-lift at rear.**	**Poor drainage in rear garden.**
Brookfield (1)	**60**	**1:123**	**4**	**Rear re-entrant corner lift.**	**Poor landscaping.**
Brookfield (2)	**50**	**1:73**	**3**	**Edge-lift all around.**	**Plumbing leaks.**
Brookfield (3)	**50**	**1:103**	**3**	**Edge lift on 3 sides.**	**Pipe leaks.**

Brookfield (4)	**50**	**1:42**	**4**	**Edge lift on 3 sides.**	**Poor drainage/Pipe leak.**
Brookfield (5)	**40**	**1:125**	**3**	**Front of house lifted.**	**Poor drainage.**
Caroline Springs (1)	**90**	**1:42**	**4**	**Severe edge-lift and settlement.**	**Tree drying/plumbing leak(s)**
Caroline Springs (2)	**70**	**1:67**	**4**	**Edge lift on all sides.**	**Poor landscaping/Plumbing leaks**
Craigieburn (1)	**10**	**1:142**	**2**	**Minor slab distortion.**	**Seasonal effects.**
Craigieburn (2)	**30**	**1:197**	**2**	**Minor slab distortions**	**Seasonal effects.**
Craigieburn (3)	**30**	**1:151**	**3**	**Re-entrant corner lift.**	**Poor landscaping.**
Derrimut	**30**	**1:176**	**3**	**Front west corner-lift.**	**Plumbing leak.**
Eynesbury (1)	**30**	**1:122**	**3**	**Rear of garage lift.**	**Plumbing leak.**
Eynesbury (2)	**10**	**1:195**	**2**	**Minor slab distortion.**	**Undetected.**
Greenvale	**20**	**1:142**	**3**	**Edge lift on West side**	**Poor site drainage.**
Melton (1)	**20**	**1:126**	**2**	**Minor slab distortion.**	**Seasonal effect.**
Melton (2)	**10**	**1:93**	**1**	**Minor slab distortion**	**Seasonal effects.**
Melton (3)	**10**	**1:139**	**3**	**Moderate slab distortion.**	**Plumbing leak.**
Melton (4)	**10**	**1:241**	**2**	**Front and of house has lifted.**	**Plumbing leak/Poor drainage.**
Melton (5)	**50**	**1:97**	**4**	**Front and rear lift.**	**Poor site drainage**
Melton (6)	**40**	**1:107**	**3**	**Slab has lifted on 3 sides.**	**Poor site drainage.**
Melton (7)	**20**	**1:150**	**2**	**Front and rear slab lift.**	**Poor site drainage.**
Melton (8)	**40**	**1:142**	**3**	**Front wall lift.**	**Poor site drainage.**
Melton South	**30**	**1:143**	**3**	**Front and rear corner lift.**	**Plumbing leaks.**
Melton West (1)	**40**	**1:180**	**4**	**Severe rear edge-lift.**	**Plumbing leaks.**
Melton West (2)	**100**	**1:61**	**4**	**Sharp lift on 3 sides.**	**Plumbing leaks.**
Melton West (3)	**40**	**1:74**	**4**	**Re-entrant corner lift.**	**Poor landscaping.**
Melton West (4)	**40**	**1:171**	**3**	**Front half of house lift.**	**Poor drainage.**
Melton West (5)	**60**	**1:77**	**4**	**Lift in rear half of house.**	**Poor drainage.**

Melton West (6)	**50**	**1:95**	**4**	**Front and west side of house lift.**	**Poor drainage.**
Melton West (7)	**10**	**1:135**	**2**	**Very minor movement.**	**Undetected.**
Melton West (8)	**50**	**1:161**	**4**	**Rear 30% of house lifted.**	**Poor drainage and rear flooding.**
Melton West (9)	**20**	**1:149**	**3**	**Front and rear lift**	**Poor drainage.**
Melton West (10)	**10**	**1:135**	**2**	**Minor slab distortion.**	**Seasonal effect.**
Pt Cook (1)	**20**	**1:285**	**2**	**Minor front corner lift.**	**Transition of drought to flood.**
Tarneit	**20**	**1:153**	**3**	**Minor front settlement.**	**Drought drying/poor landscaping**
Taylors Hill (1)	**20**	**1:144**	**2**	**Minor lift on N. W. front corner.**	**Plumbing leaks.**
Taylors Hill (2)	**30**	**1:120**	**3**	**Corner lift near removed tree.**	**Rebound after tree removal.**
Truganina	**40**	**1:71**	**4**	**Edge lift on N. and S. side.**	**Leaky pipes and poor drainage.**
Wyndham Vale(1)	**70**	**1:82**	**4**	**Rear 1/3 house lift.**	**Poor site drainage.**
Wyndham Vale(2)	**30**	**1:109**	**3**	**Differential movements.**	**Undetected.**

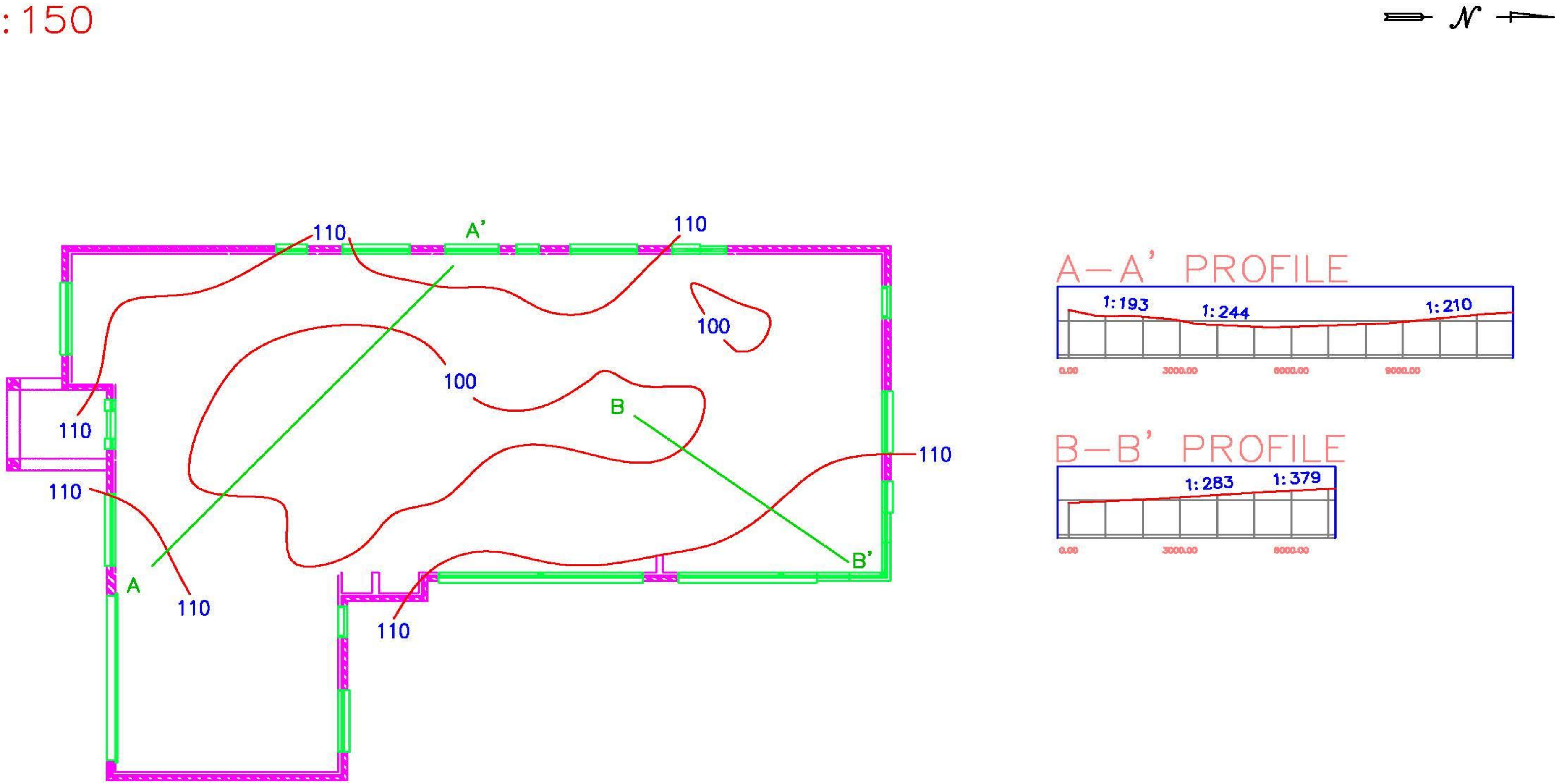
<u>SUMMARY FOR WAFFLE SLABS INVESTIGATED</u>

Causes of damage	Number affected	Percentage affected
Poor drainage.	17	40%
Plumbing leaks.	14	33%
Poor landscaping.	5	12%
Seasonal effects.	5	12%
Drought effects.	2	5%
Tree effects.	2	5%
Undetected.	3	7%

*** Number of houses with 2 distinct causes = 6.**

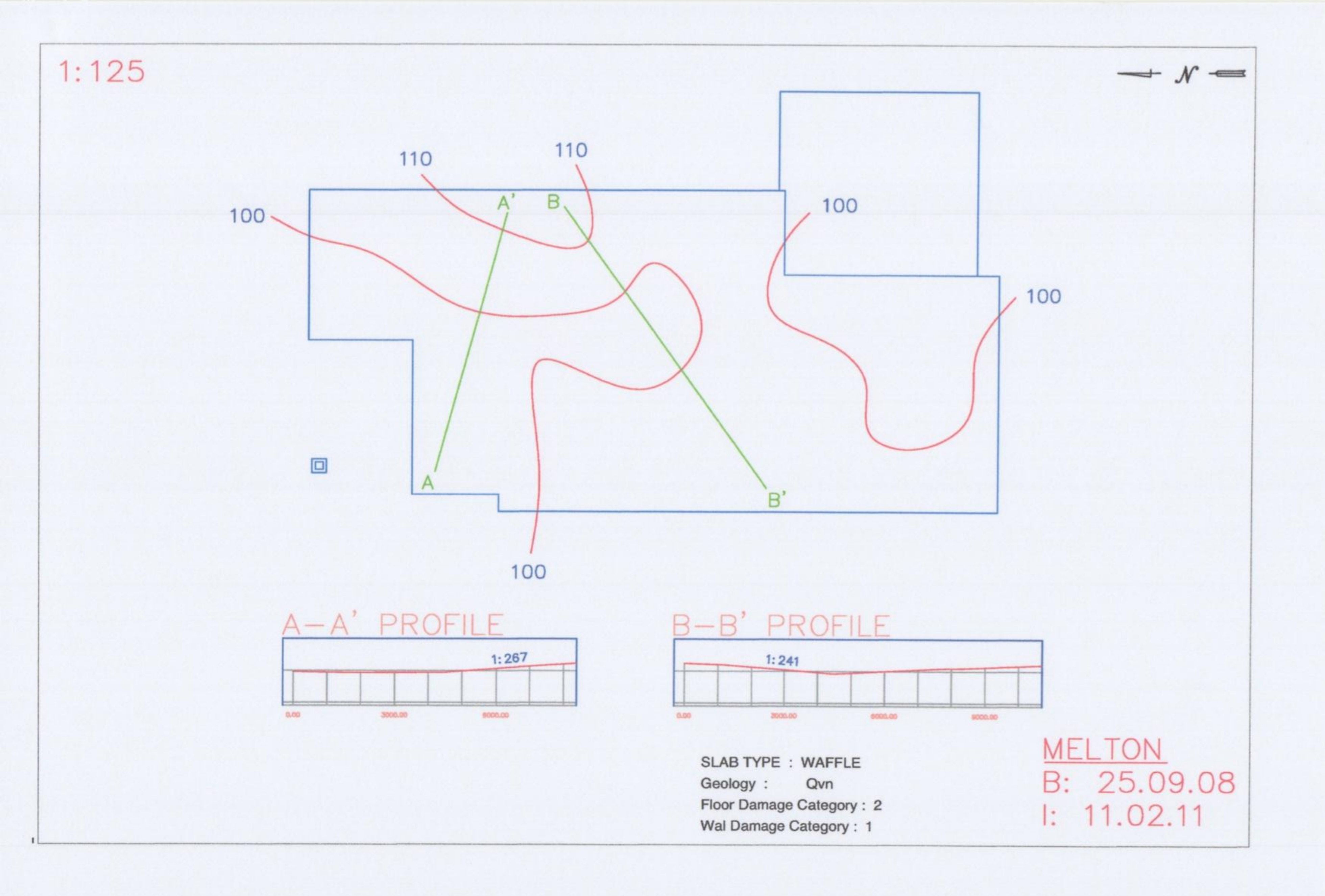
**** Damage could have been reduced if site classifications had considered a 'E' alternative as shown in AS2870 table D1.**

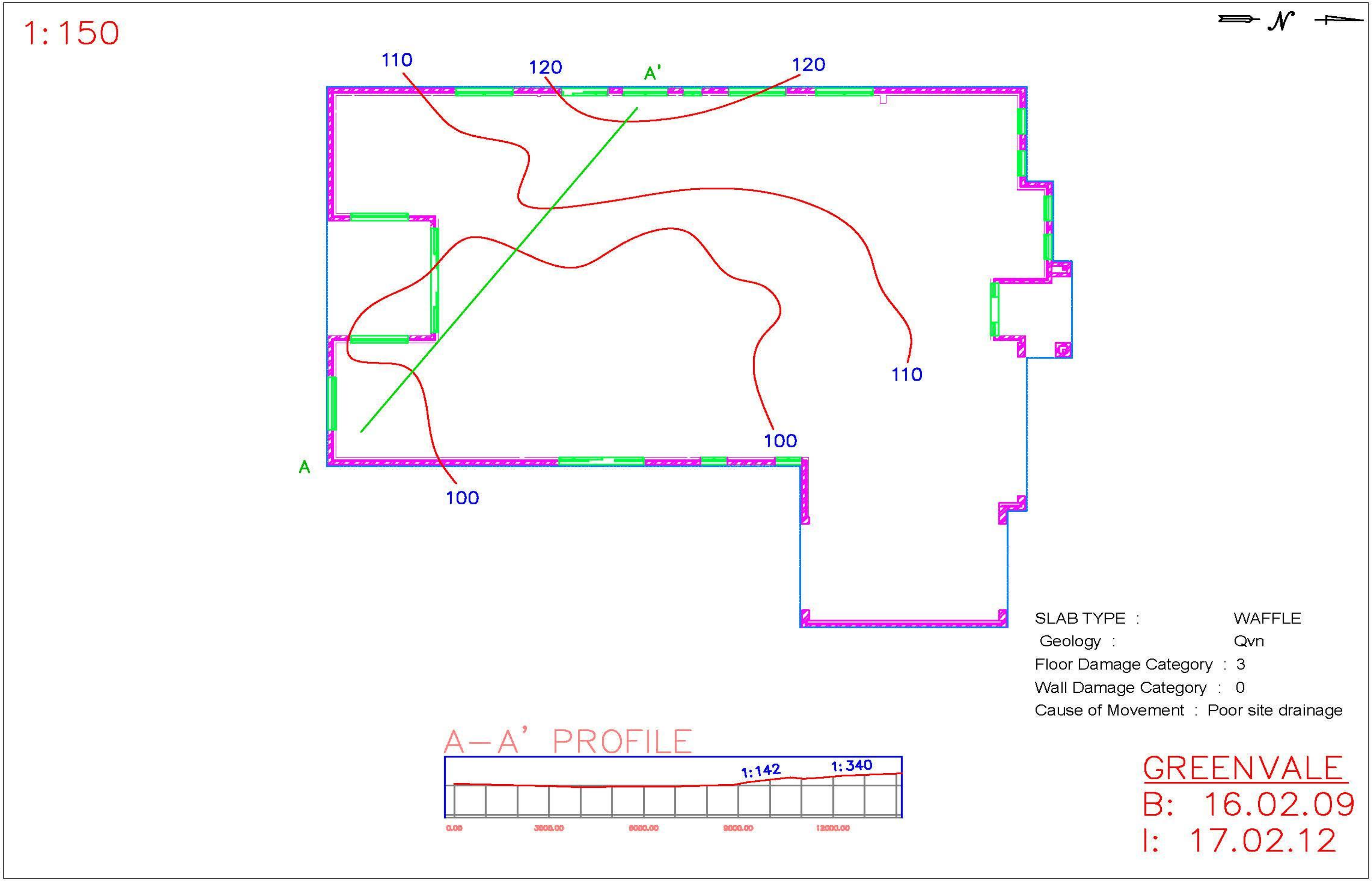
1:150

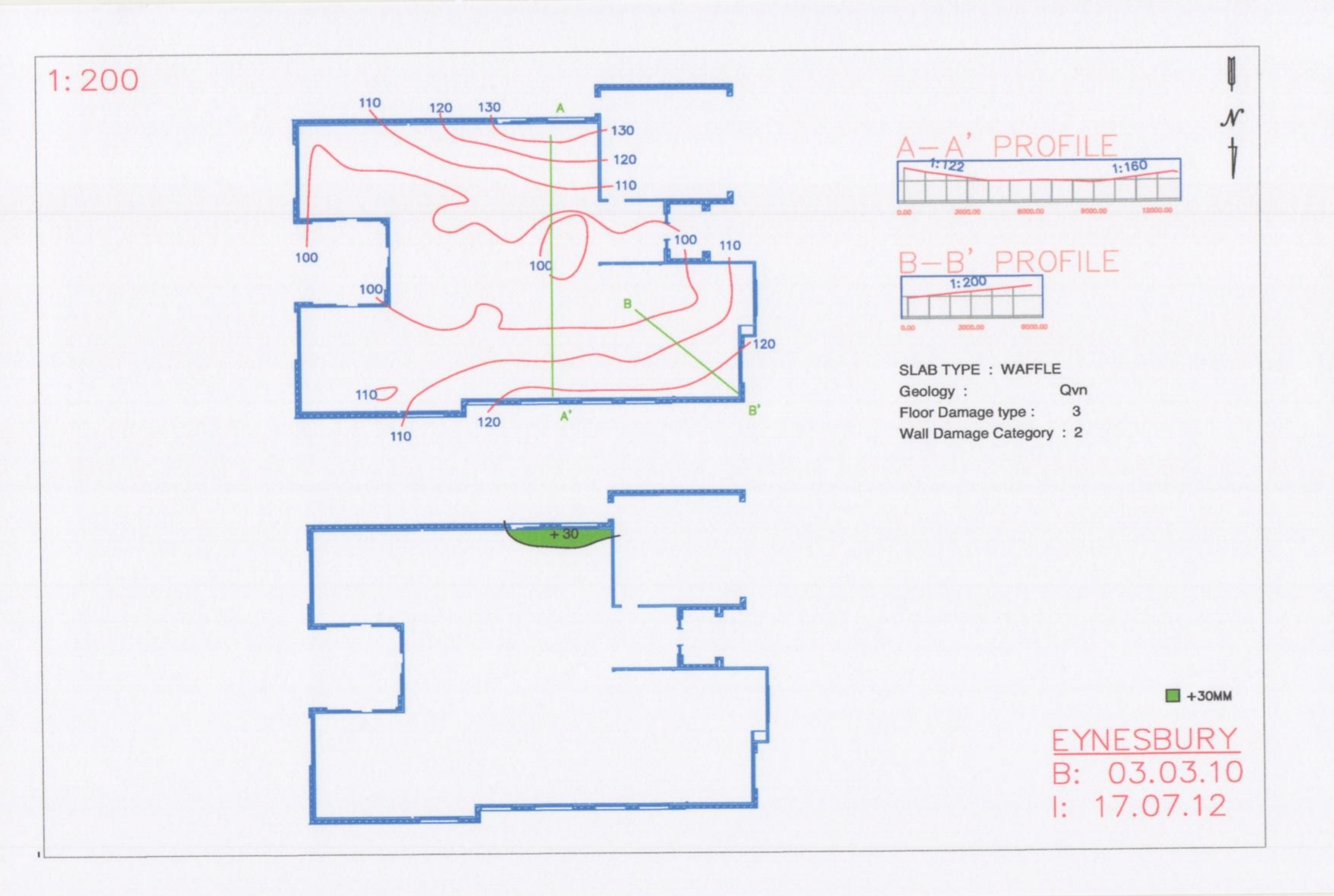


SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 1
Wall Damage Category : 1
Cause of Movement : Poor Site Drainage

MELTON
B: 01.07.09
I: 07.09.10


1:125
N
110
110
100
A'
B
100
100
A
B'
100
A–A' PROFILE
1:267
B–B' PROFILE
1:241
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 2
Wal Damage Category : 1
MELTON
B: 25.09.08
I: 11.02.11


1:150
110
120
A'
120
110
100
A
100
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 0
Cause of Movement : Poor site drainage
A—A' PROFILE
1:142
1:340
GREENVALE
B: 16.02.09
I: 17.02.12


1: 200
110
120
130
A
130
120
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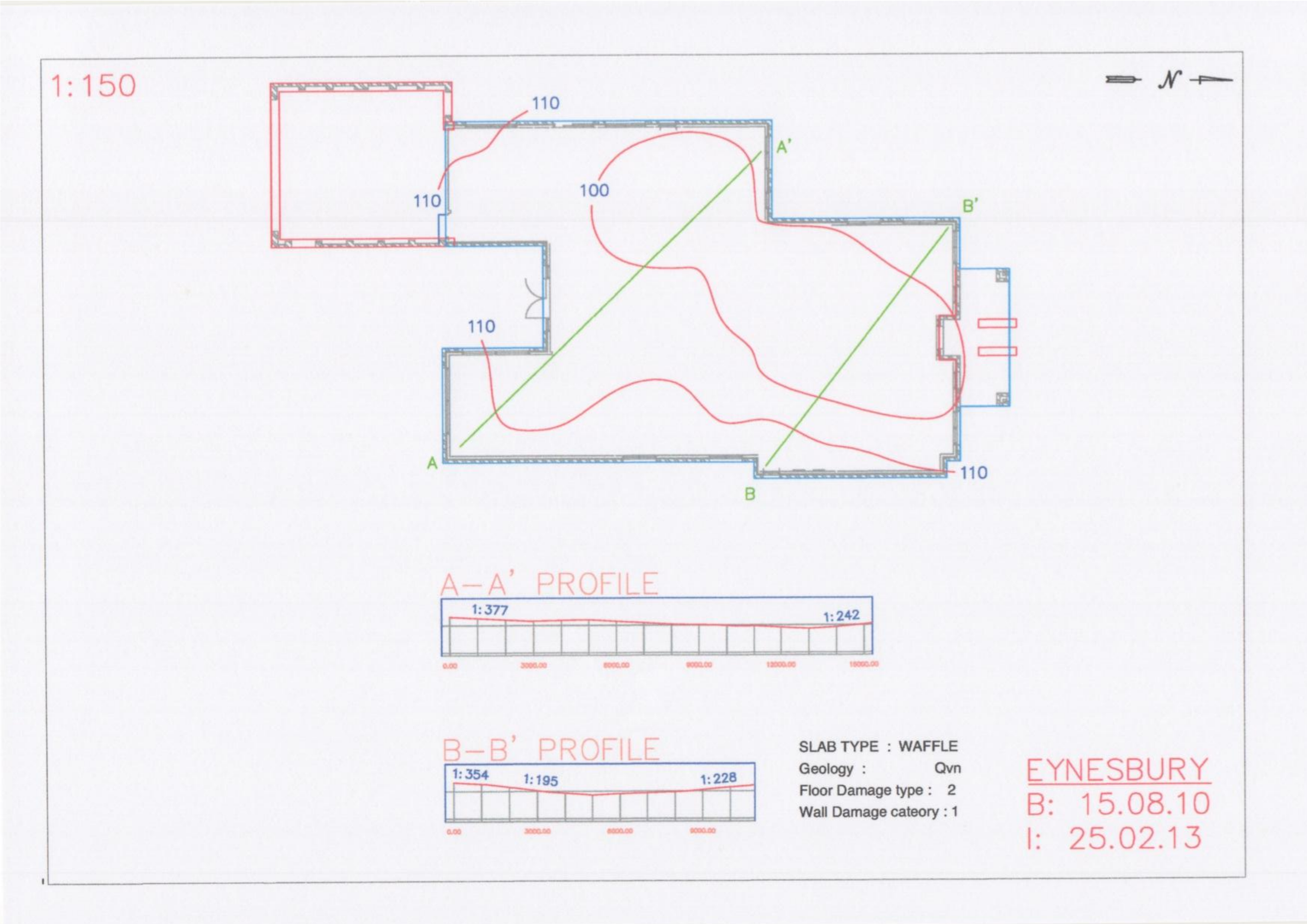
100
110
100
100
100
B
120
110
110
120
A'
B'
+ 30
A–A' PROFILE
1:122
1:160
B–B' PROFILE
1: 200
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage type : 3
Wall Damage Category : 2
+30MM
EYNESBURY
B: 03.03.10
I: 17.07.12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110
110
100
A'
B'
110
A
B
110
A-A' PROFILE
1:377
1:242
B-B' PROFILE
1:354
1:195
1:228
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage type : 2
Wall Damage cateory : 1
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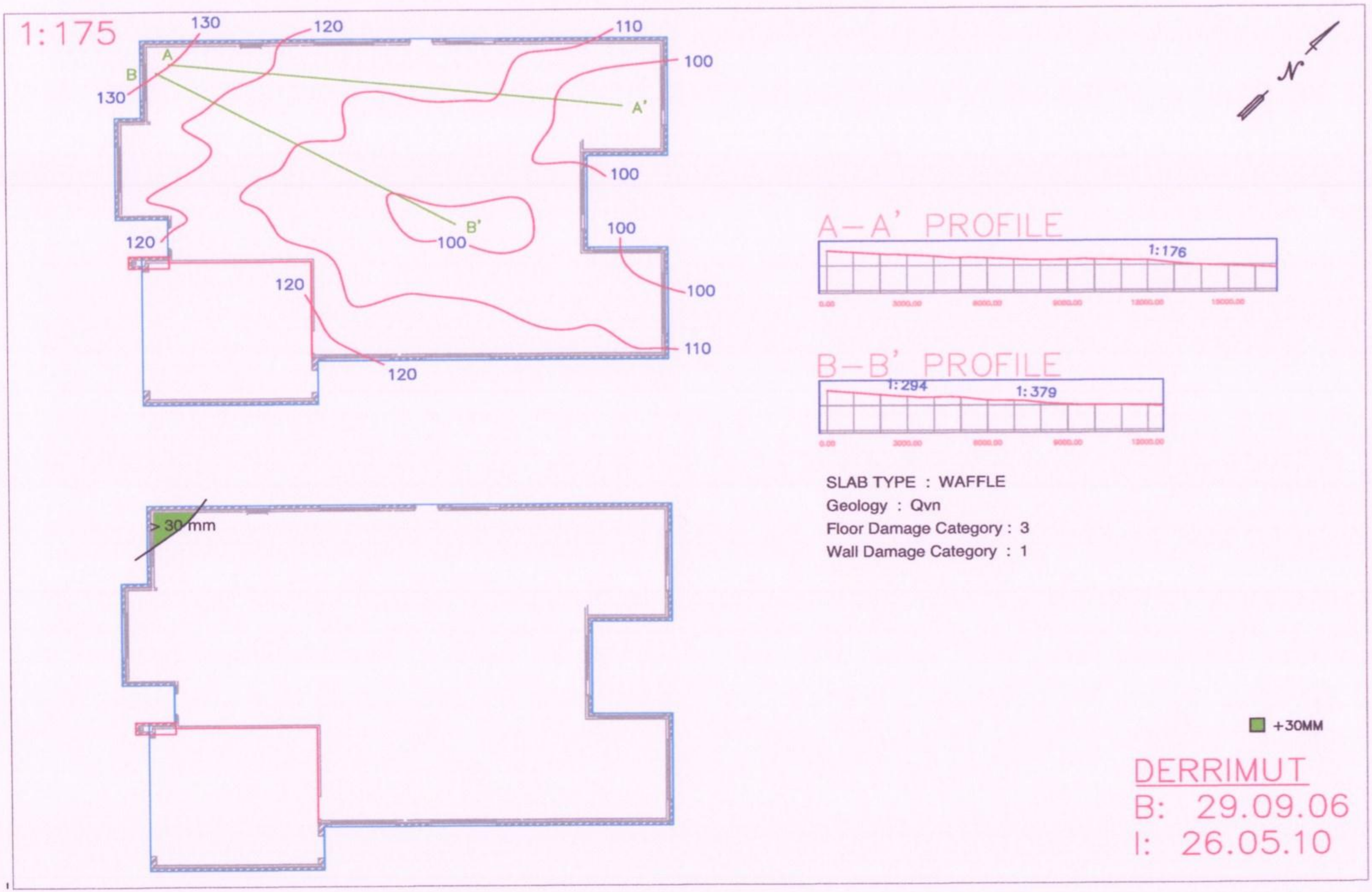
I: 25.02.13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120
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100
120
100
110
120
N
A–A' PROFILE
1:176
B–B' PROFILE
1:294
1:379
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 1
> 30 mm
+30MM
DERRIMUT
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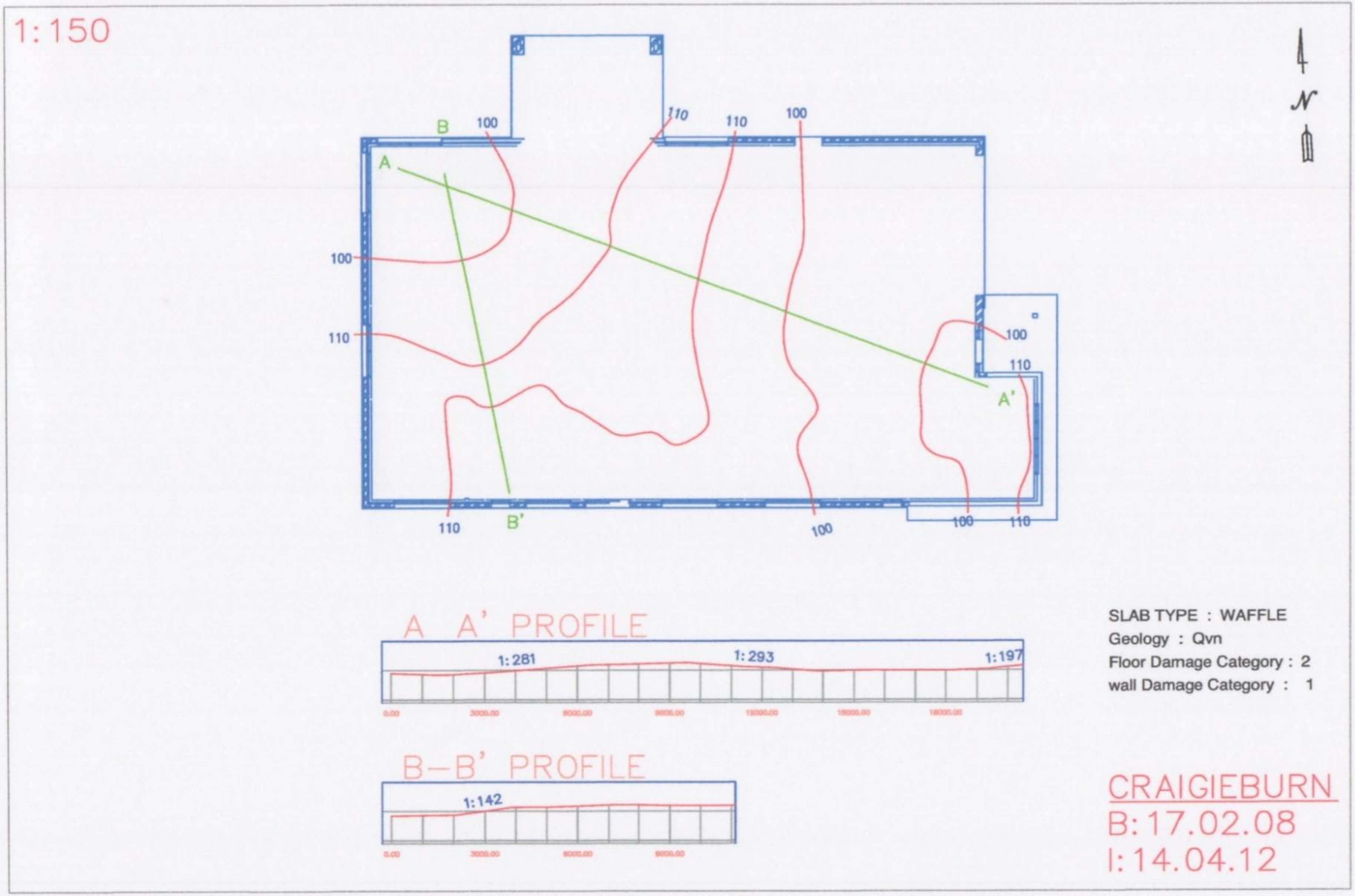
I: 26.05.10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B'
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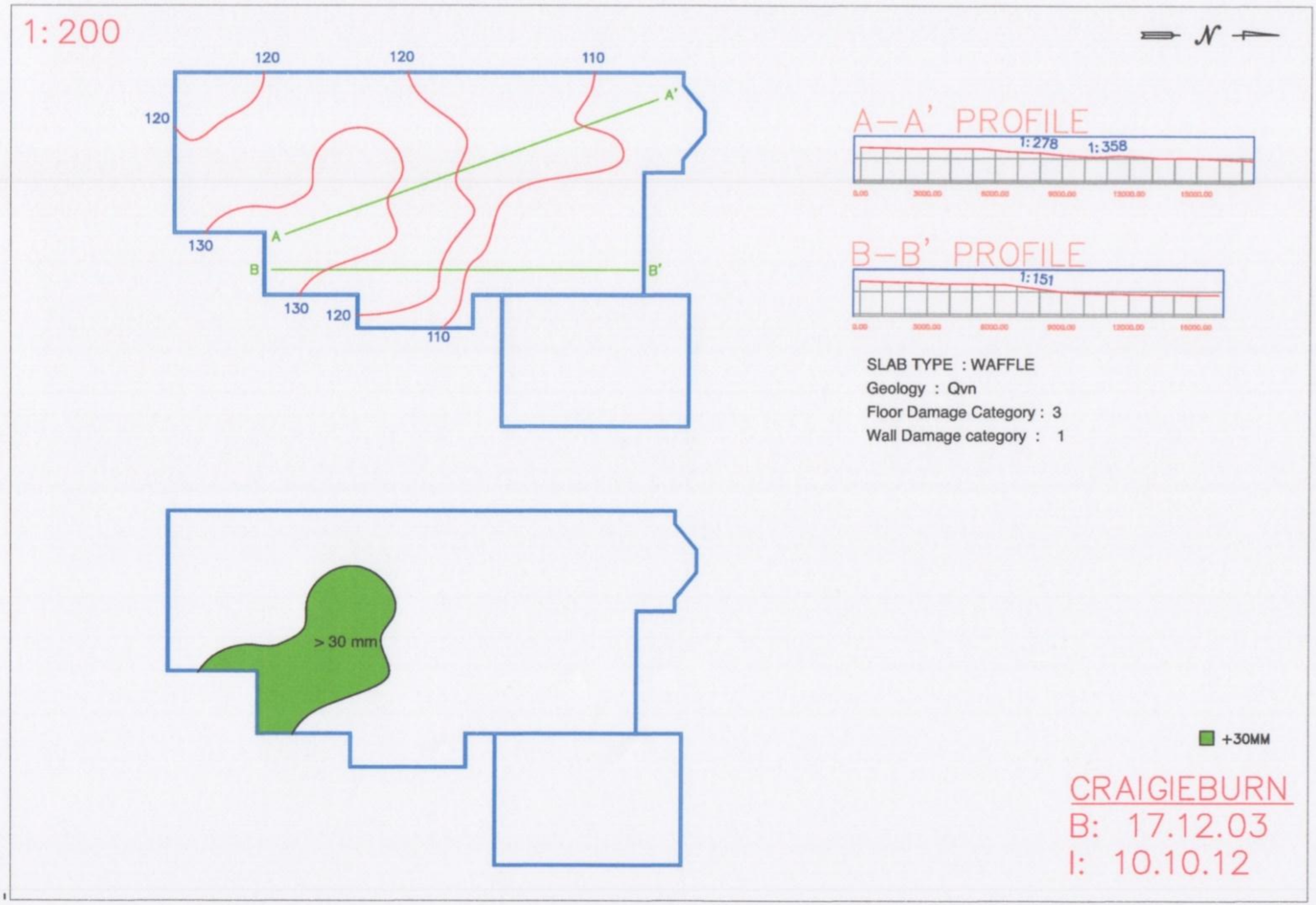
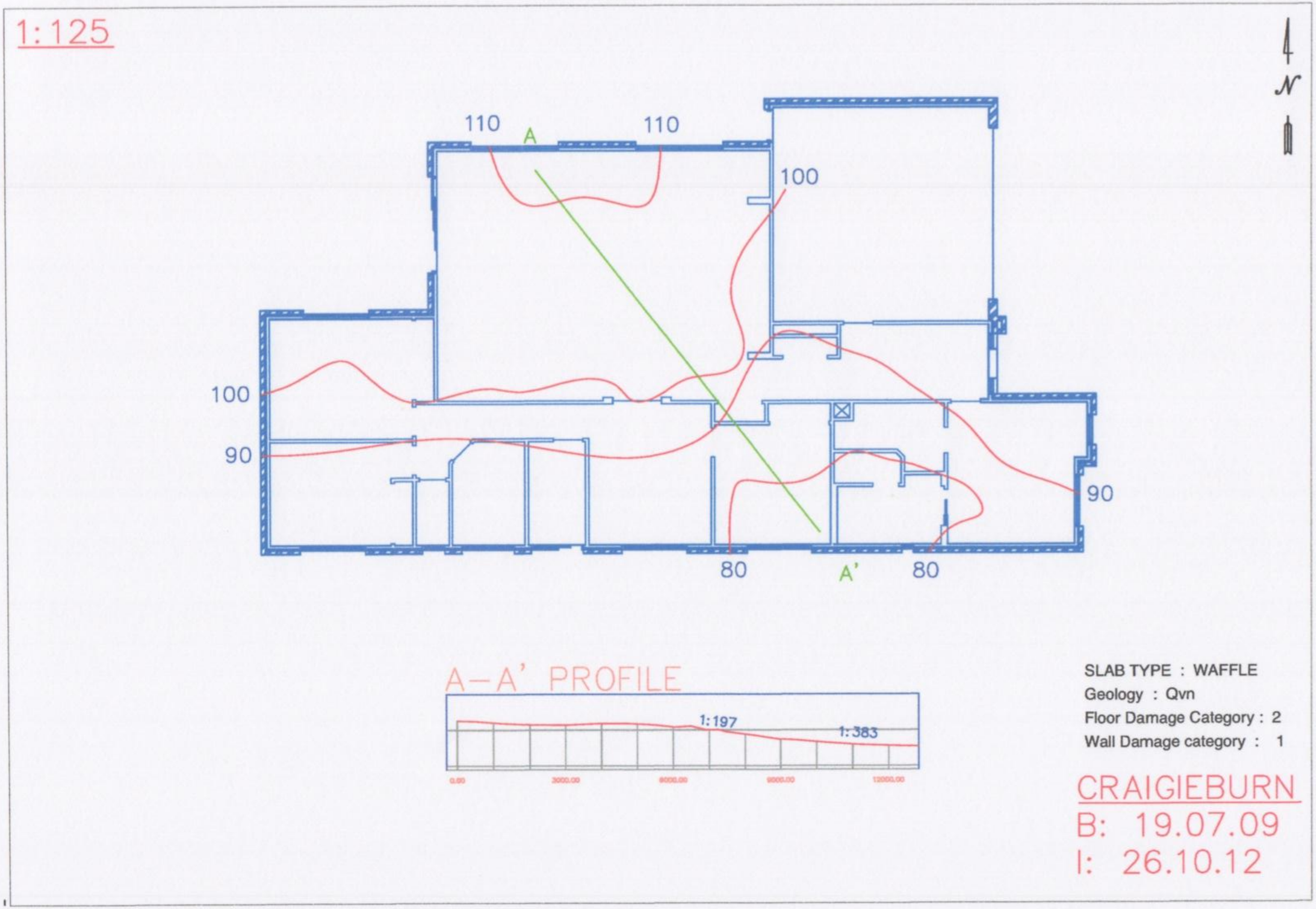
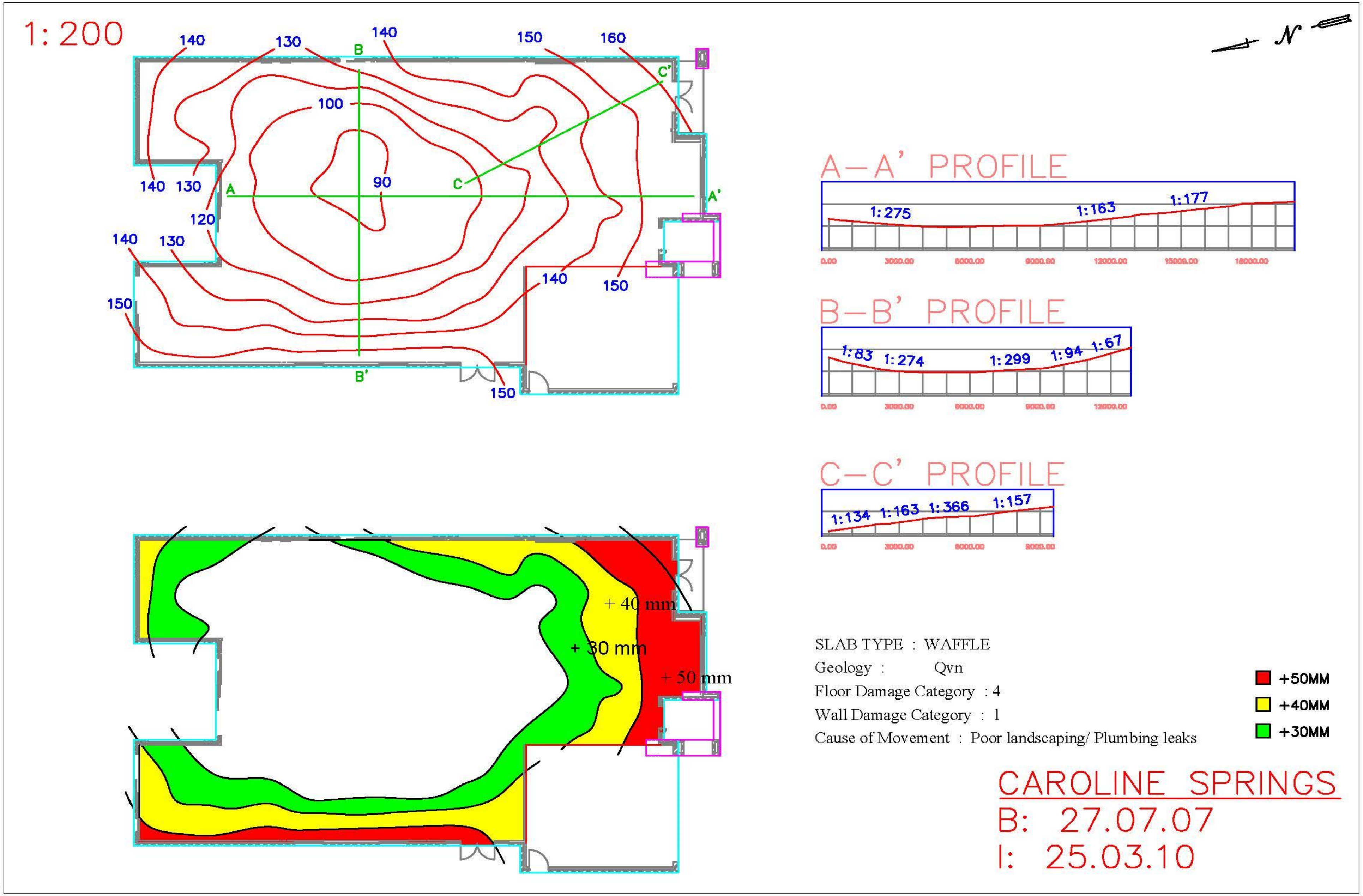
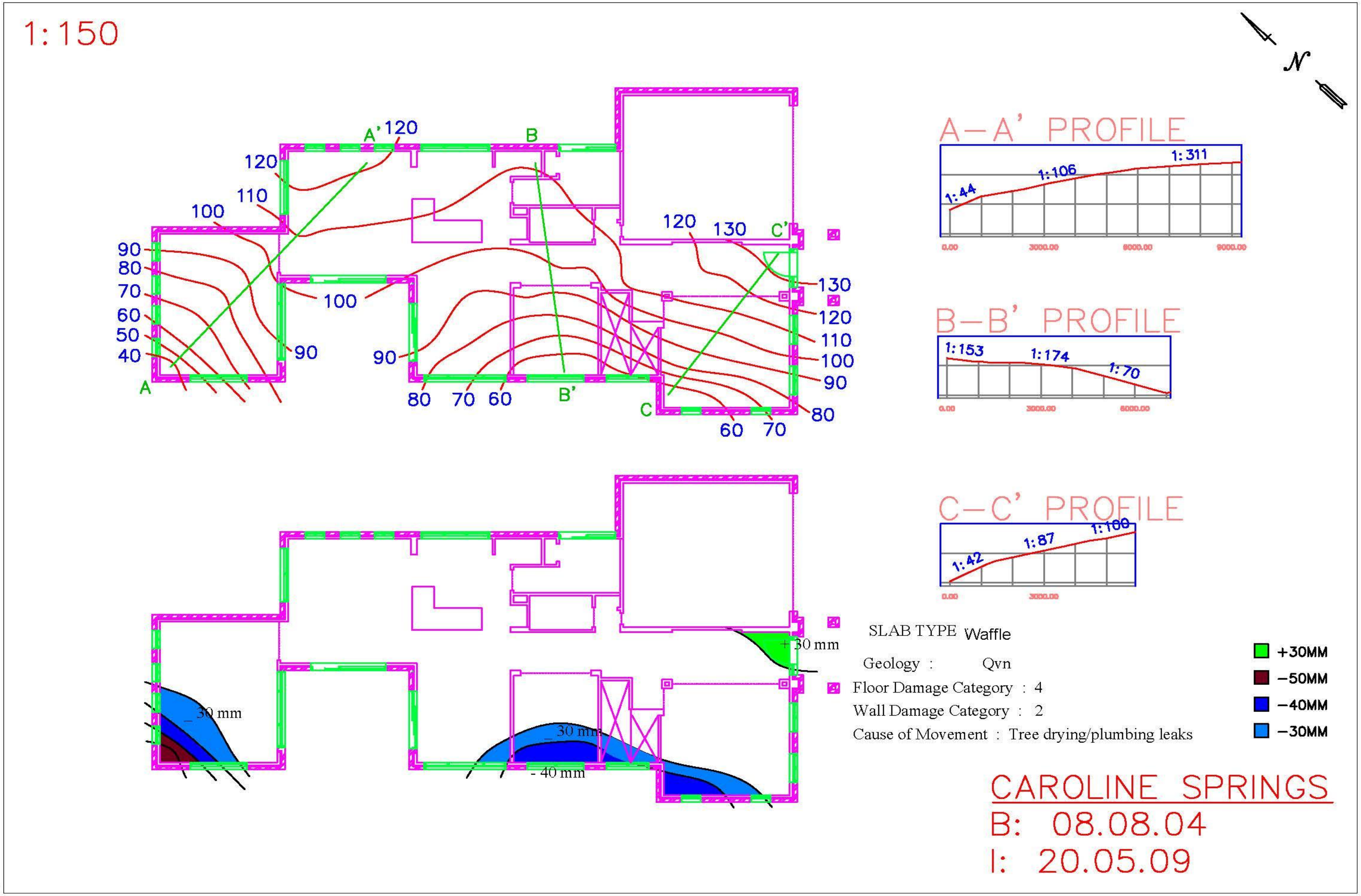
100
110
A A' PROFILE
1:281
1:293
1:197
B-B' PROFILE
1:142
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 2
wall Damage Category : 1
CRAIGIEBURN
B: 17.02.08
I: 14.04.12

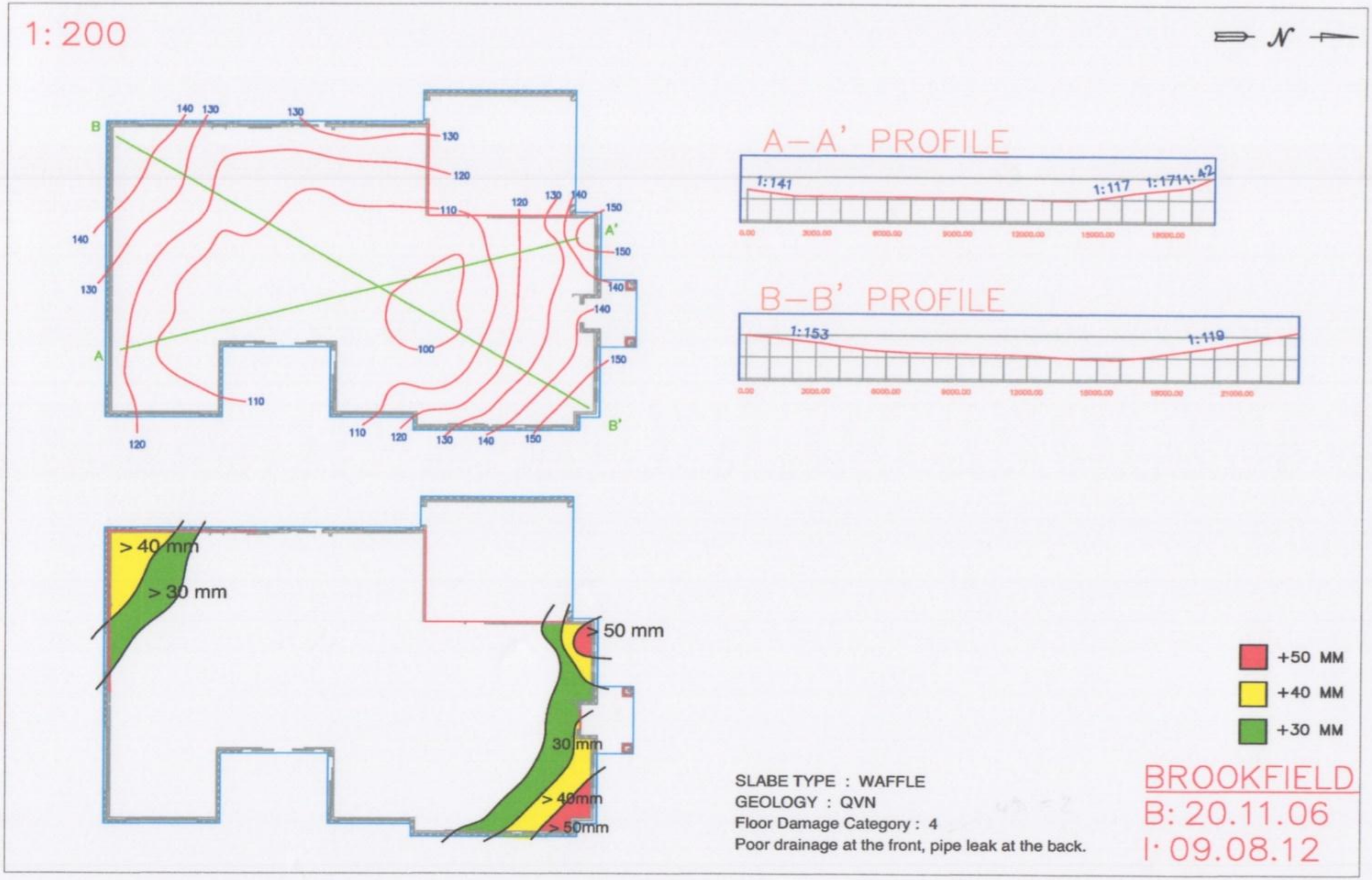


1: 200
120
120
110
120
A'
A
130
B
B'
130
120
110
A–A' PROFILE
1: 278
1: 358
B–B' PROFILE
1: 151
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage category : 1
> 30 mm
+30MM
CRAIGIEBURN
B: 17.12.03
I: 10.10.12

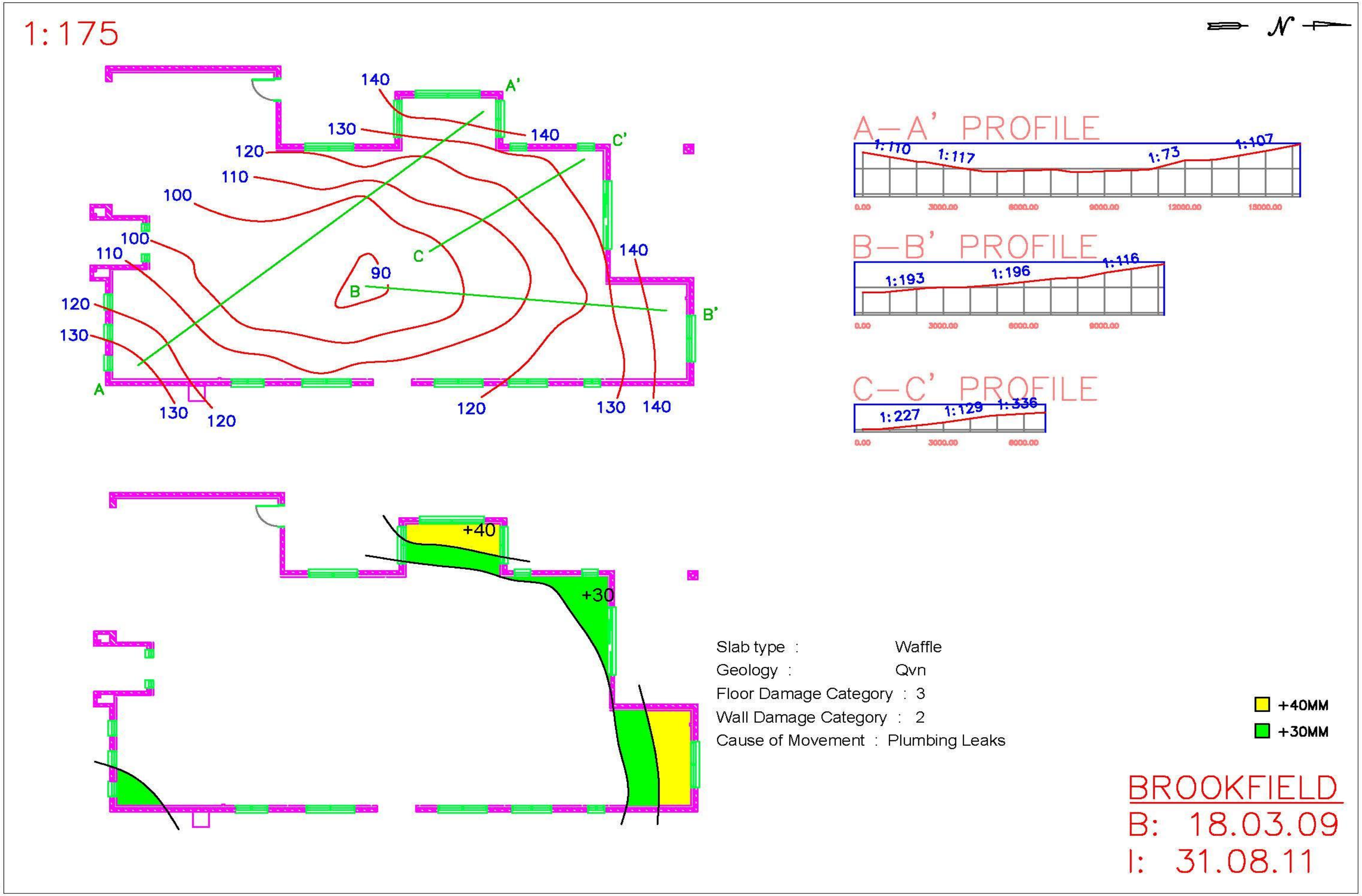

1:125
N
110
A
110
100
100
90
90
80
A'
80
A–A' PROFILE
1:197
1:383
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 2
Wall Damage category : 1
CRAIGIEBURN
B: 19.07.09
I: 26.10.12

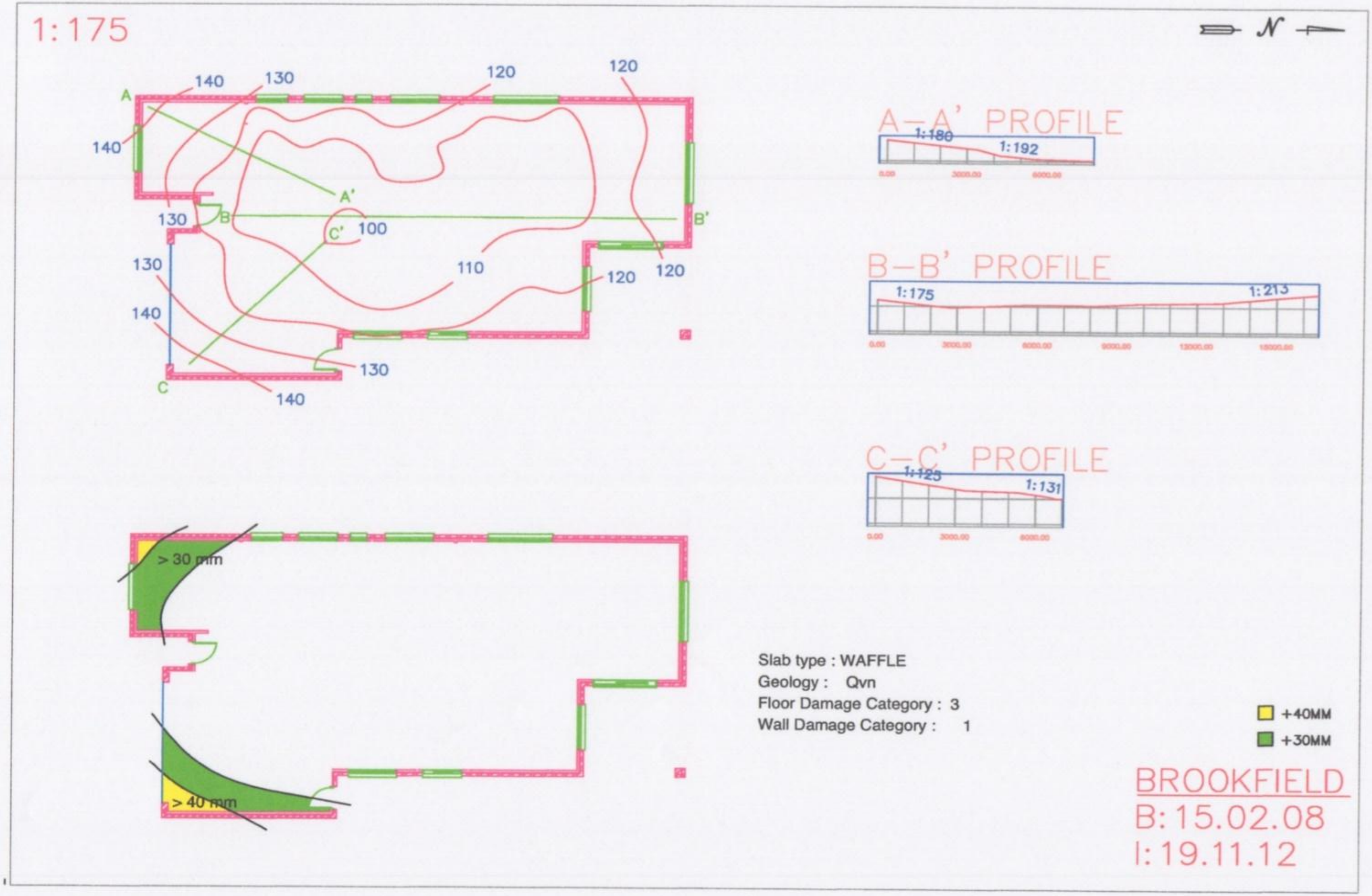

1:200
140
130
140
150
160
B
C'
100
90
C
A
A'
140 130
120
140 130
150
140
150
B'
150
A–A' PROFILE
1:275
1:163
1:177
B–B' PROFILE
1:83 1:274 1:299 1:94 1:67
C–C' PROFILE
1:134 1:163 1:366 1:157
+ 40 mm
+ 30 mm
+ 50 mm
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 4
Wall Damage Category : 1
Cause of Movement : Poor landscaping/ Plumbing leaks
+50MM
+40MM
+30MM
CAROLINE SPRINGS
B: 27.07.07
I: 25.03.10

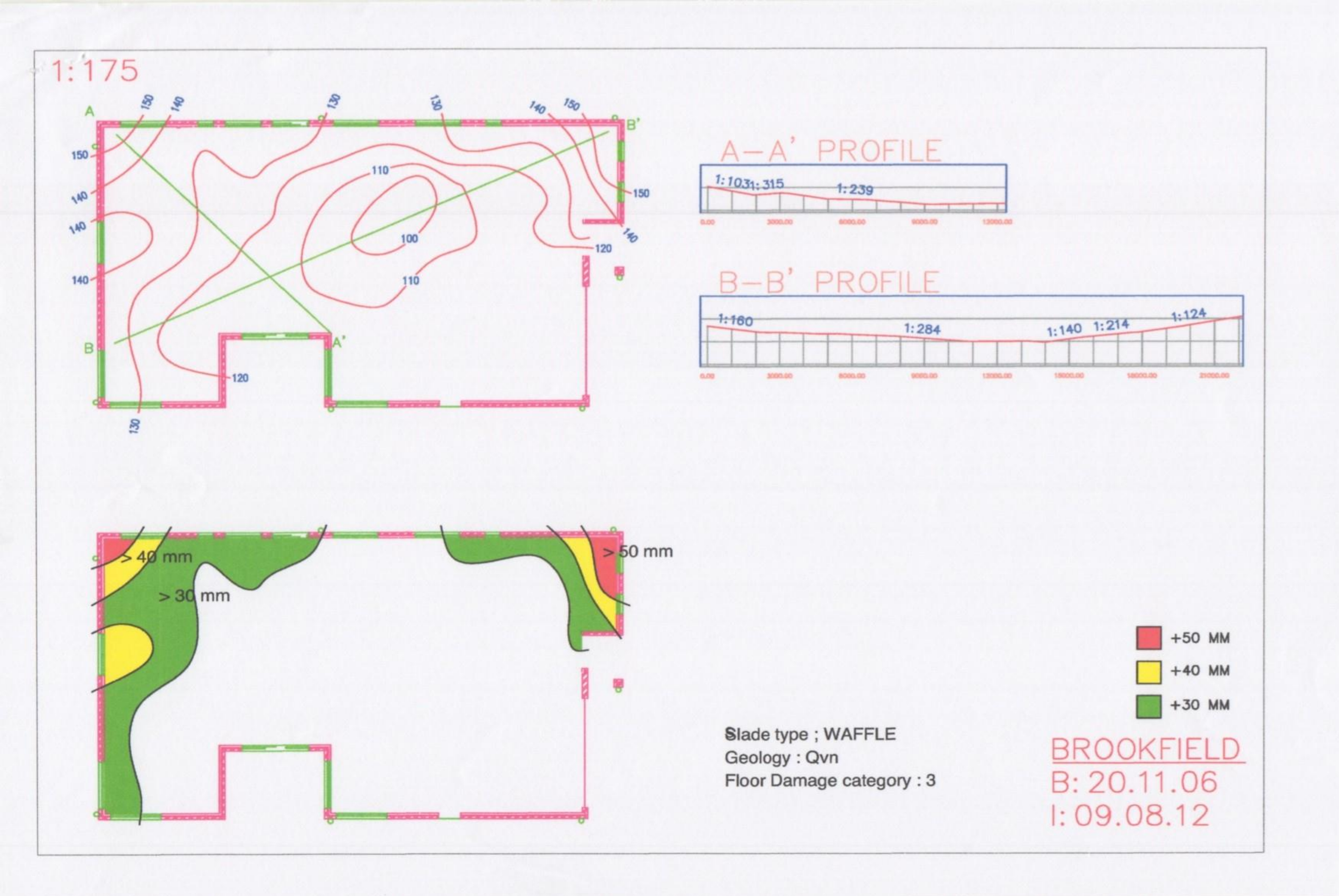

1:150
N
A–A' PROFILE
1:44
1:106
1:311
B–B' PROFILE
1:153
1:174
1:70
C–C' PROFILE
1:42
1:87
1:100
SLAB TYPE Waffle
Geology : Qvn
Floor Damage Category : 4
Wall Damage Category : 2
Cause of Movement : Tree drying/plumbing leaks
+30MM
−50MM
−40MM
−30MM
+ 30 mm
_ 30 mm
_ 30 mm
- 40 mm
CAROLINE SPRINGS
B: 08.08.04
I: 20.05.09

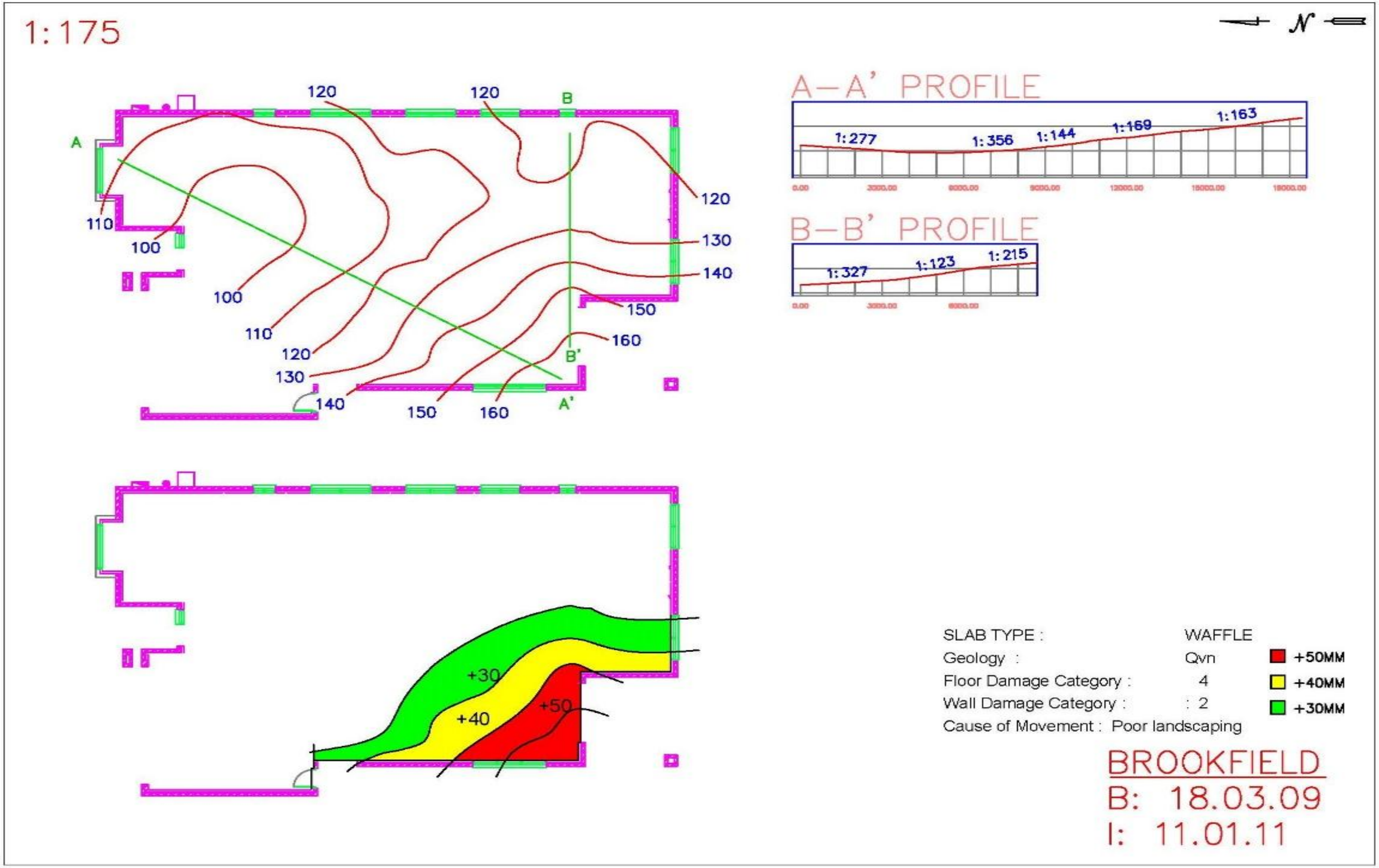


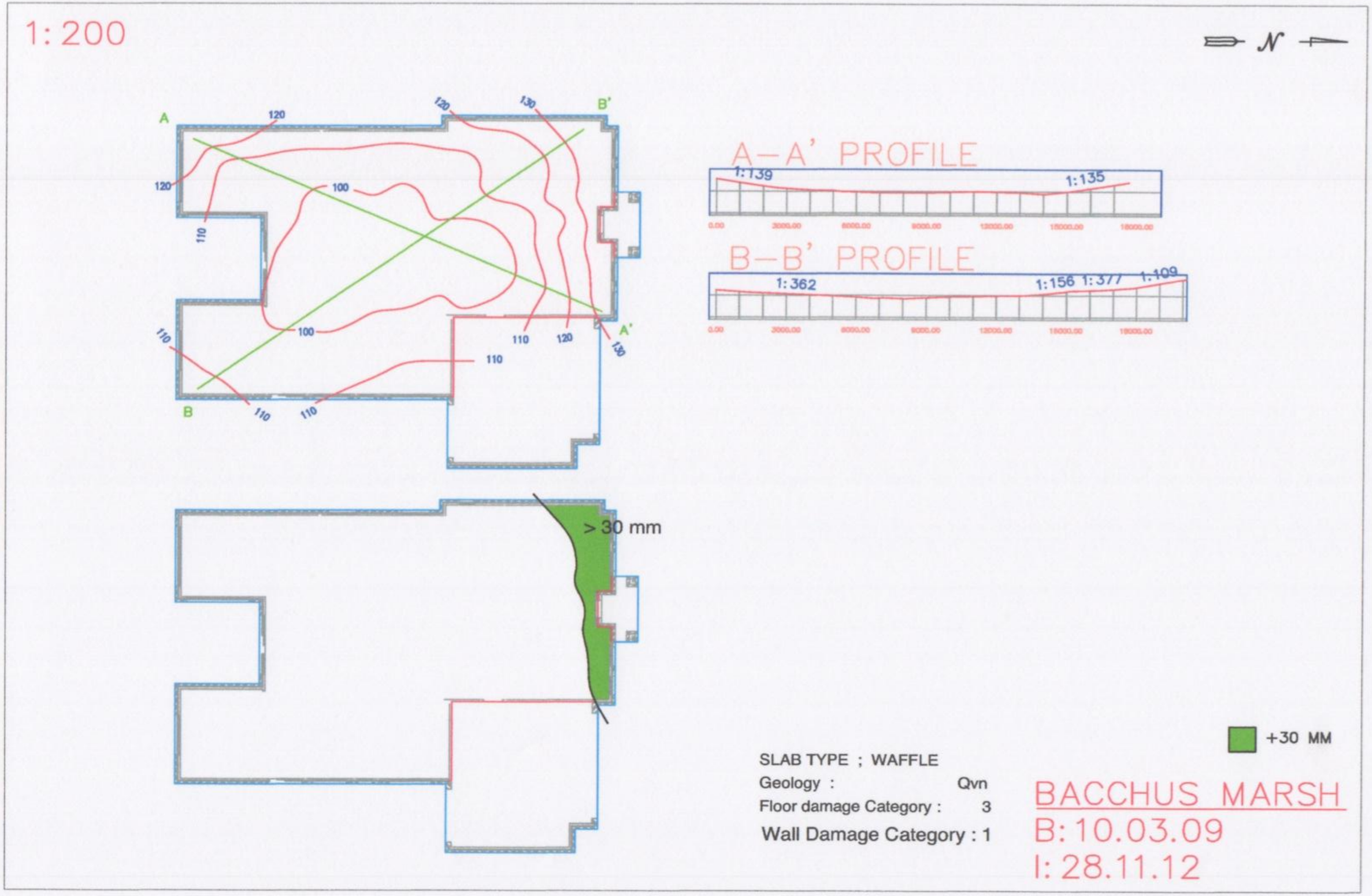
1: 200
N
A–A' PROFILE
B–B' PROFILE
> 40 mm
> 30 mm
> 50 mm
30 mm
> 40mm
> 50mm
+50 MM
+40 MM
+30 MM
SLABE TYPE : WAFFLE
GEOLOGY : QVN
Floor Damage Category : 4
Poor drainage at the front, pipe leak at the back.
BROOKFIELD
B: 20.11.06
I· 09.08.12

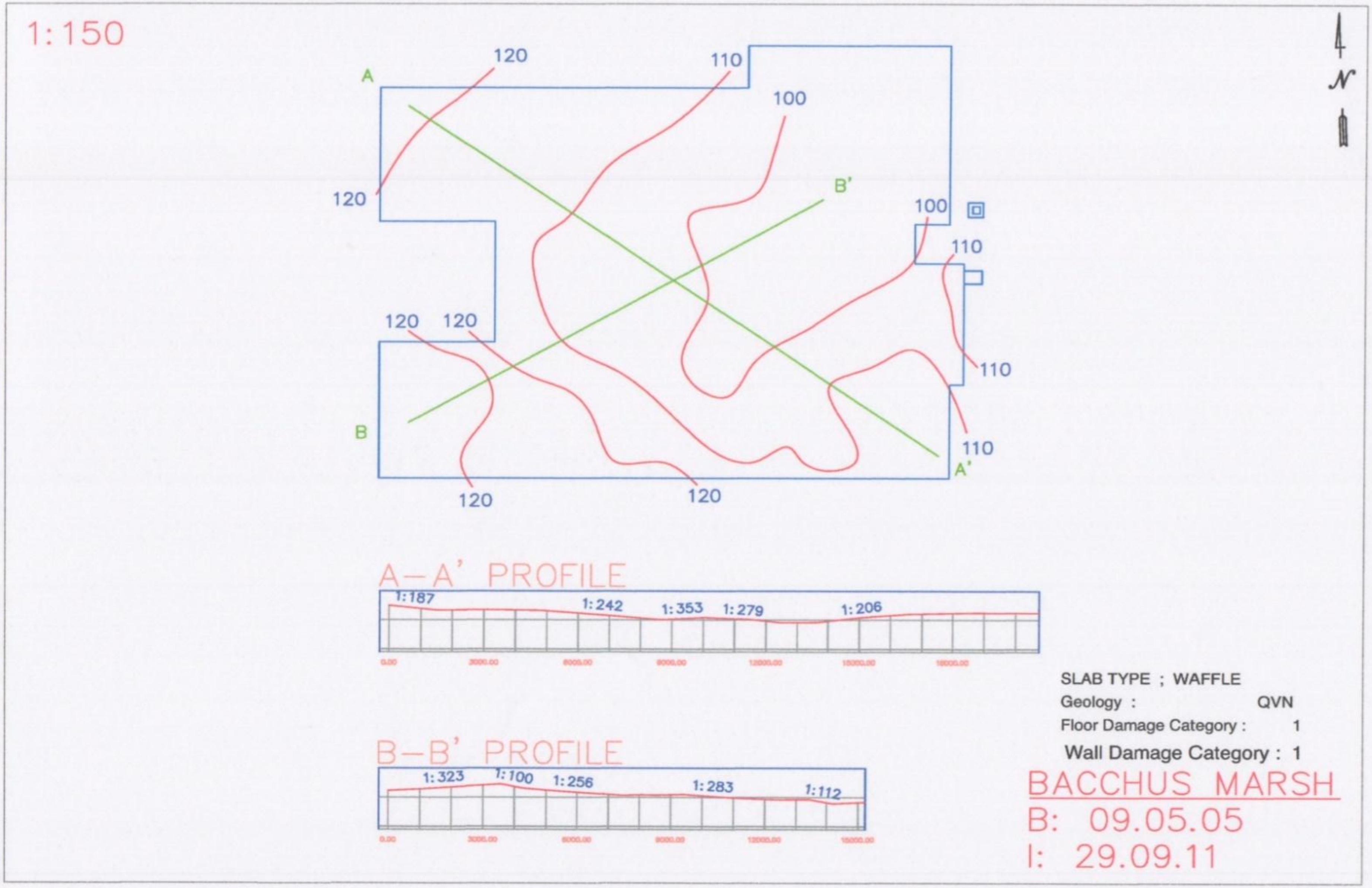

1:175
N
A–A' PROFILE
1:110
1:117
1:73
1:107
B–B' PROFILE
1:193
1:196
1:116
C–C' PROFILE
1:227
1:129
1:336
A
A'
B
B'
C
C'
90
100
110
120
130
140
+40
+30
Slab type : Waffle
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 2
Cause of Movement : Plumbing Leaks
+40MM
+30MM
BROOKFIELD
B: 18.03.09
I: 31.08.11


1:175
140
130
120
120
A
140
A'
130
B
B'
C'
100
130
110
120
120
140
130
C
140
A–A' PROFILE
1:180
1:192
B–B' PROFILE
1:175
1:213
C–C' PROFILE
1:125
1:131
> 30 mm
> 40 mm
Slab type : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 1
+40MM
+30MM
BROOKFIELD
B: 15.02.08
I: 19.11.12

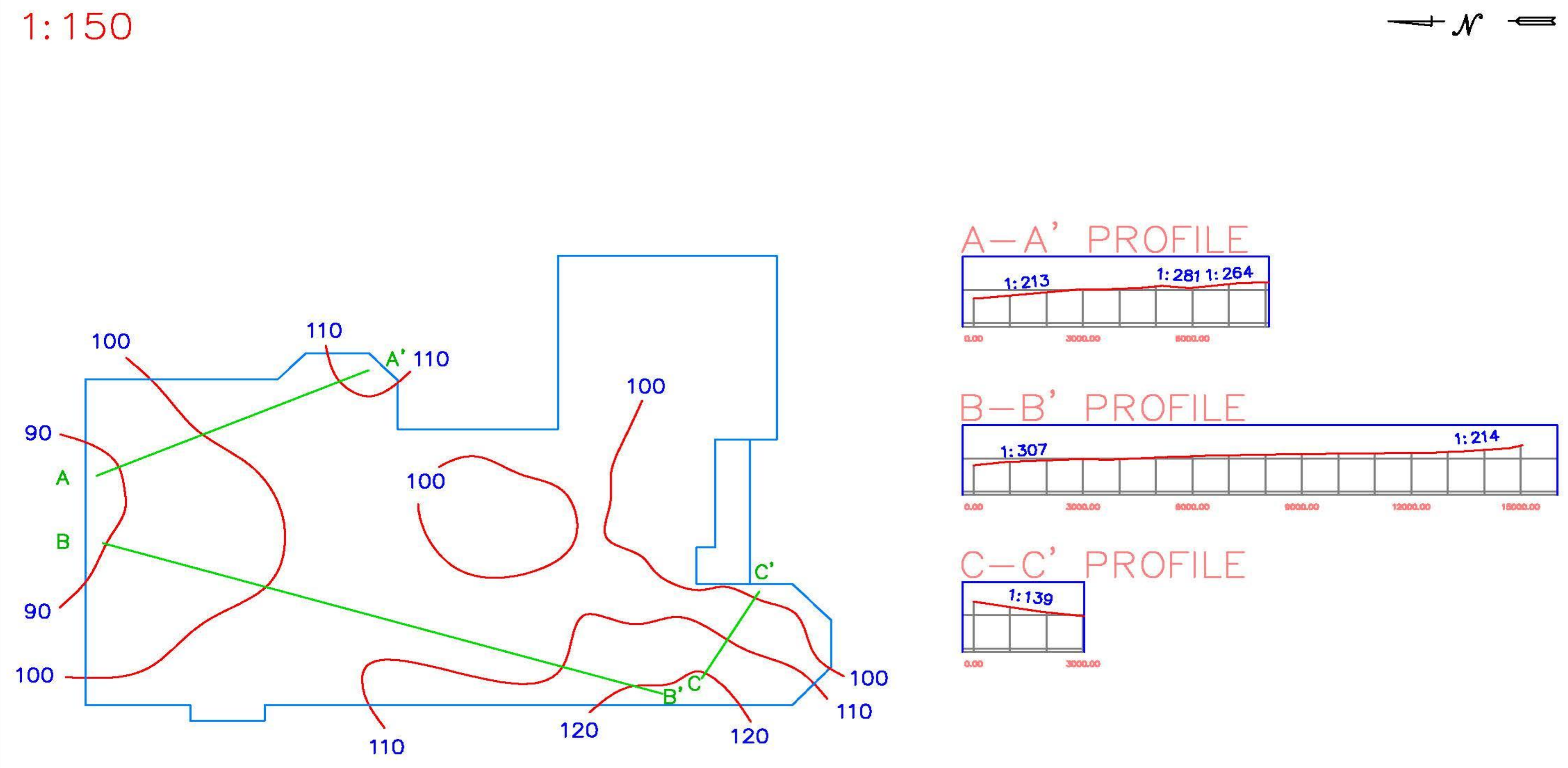

1:175
A-A' PROFILE
1:103
1:315
1:239
B-B' PROFILE
1:160
1:284
1:140
1:214
1:124
> 40 mm
> 30 mm
> 50 mm
+50 MM
+40 MM
+30 MM
Slade type ; WAFFLE
Geology : Qvn
Floor Damage category : 3
BROOKFIELD
B: 20.11.06
I: 09.08.12


1:175
A–A' PROFILE
1:277
1:356
1:144
1:169
1:163
B–B' PROFILE
1:327
1:123
1:215
A
A'
B
B'
100
110
120
130
140
150
160
+30
+40
+50
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 4
Wall Damage Category : 2
Cause of Movement : Poor landscaping
+50MM
+40MM
+30MM
BROOKFIELD
B: 18.03.09
I: 11.01.11


1: 200
N
A
B'
A'
B
120
130
100
110
A–A' PROFILE
1:139
1:135
B–B' PROFILE
1:362
1:156 1:377
1:109
> 30 mm
+30 MM
SLAB TYPE ; WAFFLE
Geology : Qvn
Floor damage Category : 3
Wall Damage Category : 1
BACCHUS MARSH
B: 10.03.09
I: 28.11.12

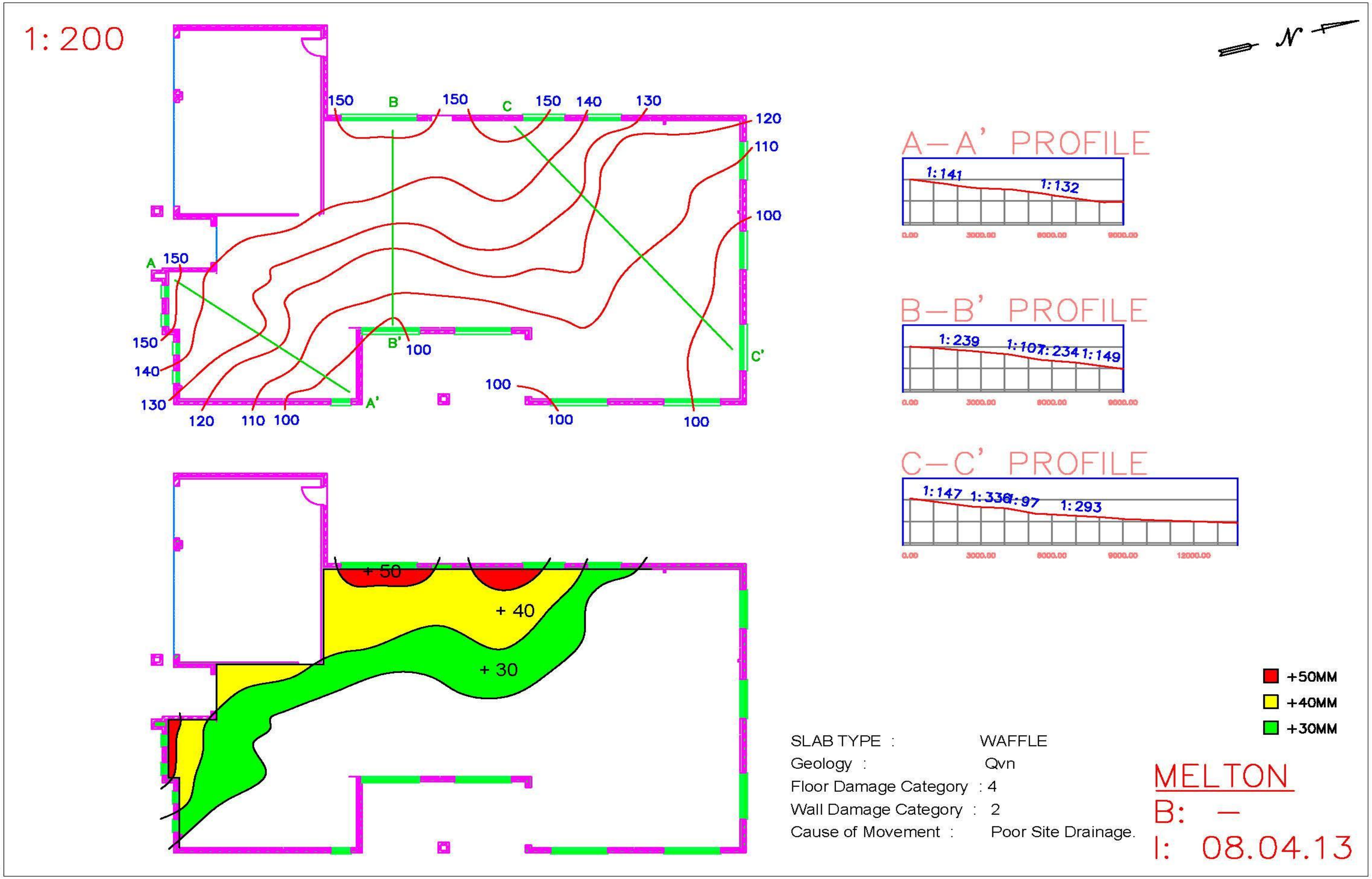


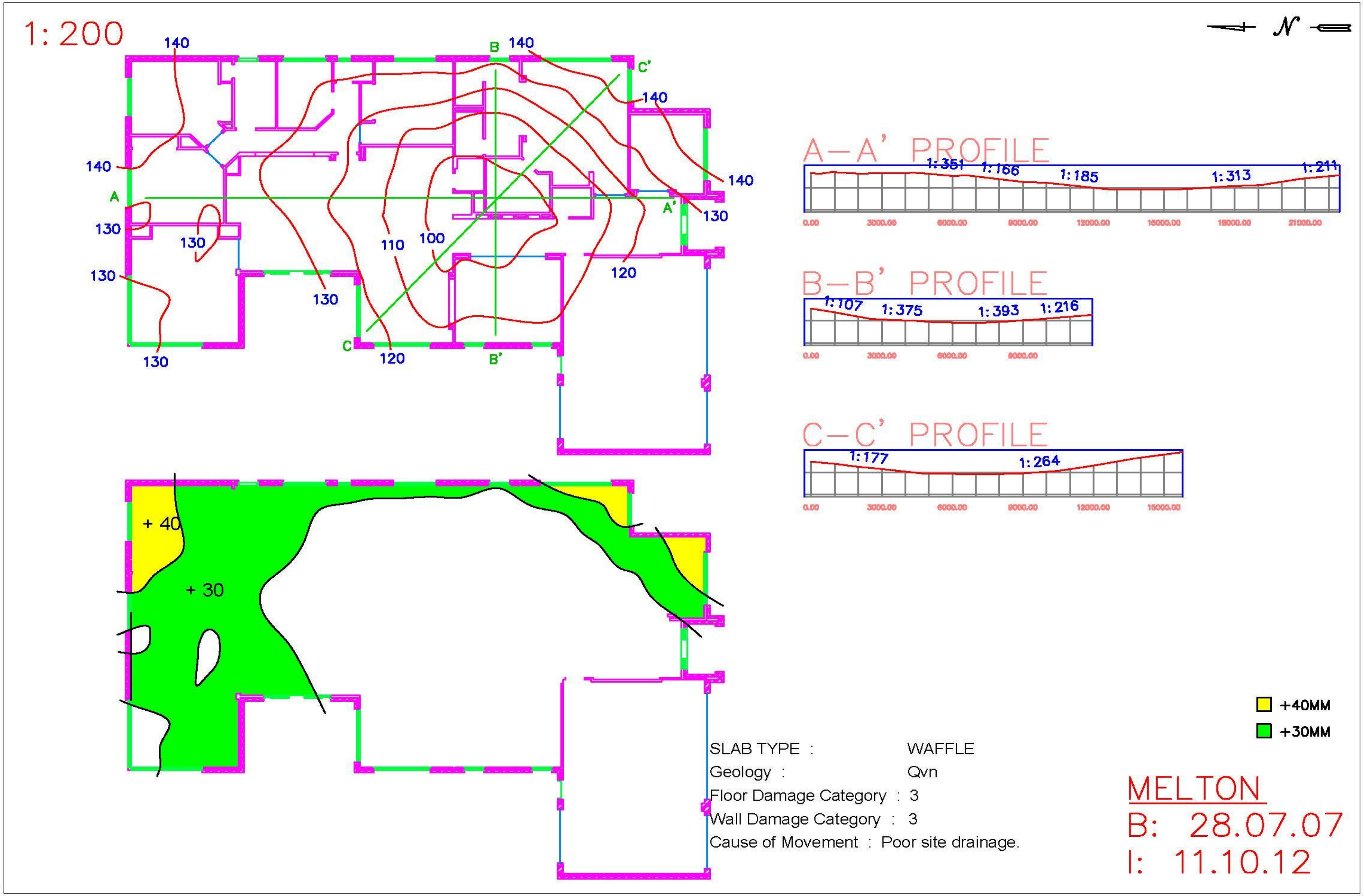
1:150
A
B
B'
A'
120
110
100
120
100
110
120
120
110
110
120
120
A–A' PROFILE
1:187
1:242
1:353
1:279
1:206
B–B' PROFILE
1:323
1:100
1:256
1:283
1:112
SLAB TYPE ; WAFFLE
Geology : QVN
Floor Damage Category : 1
Wall Damage Category : 1
BACCHUS MARSH
B: 09.05.05
I: 29.09.11

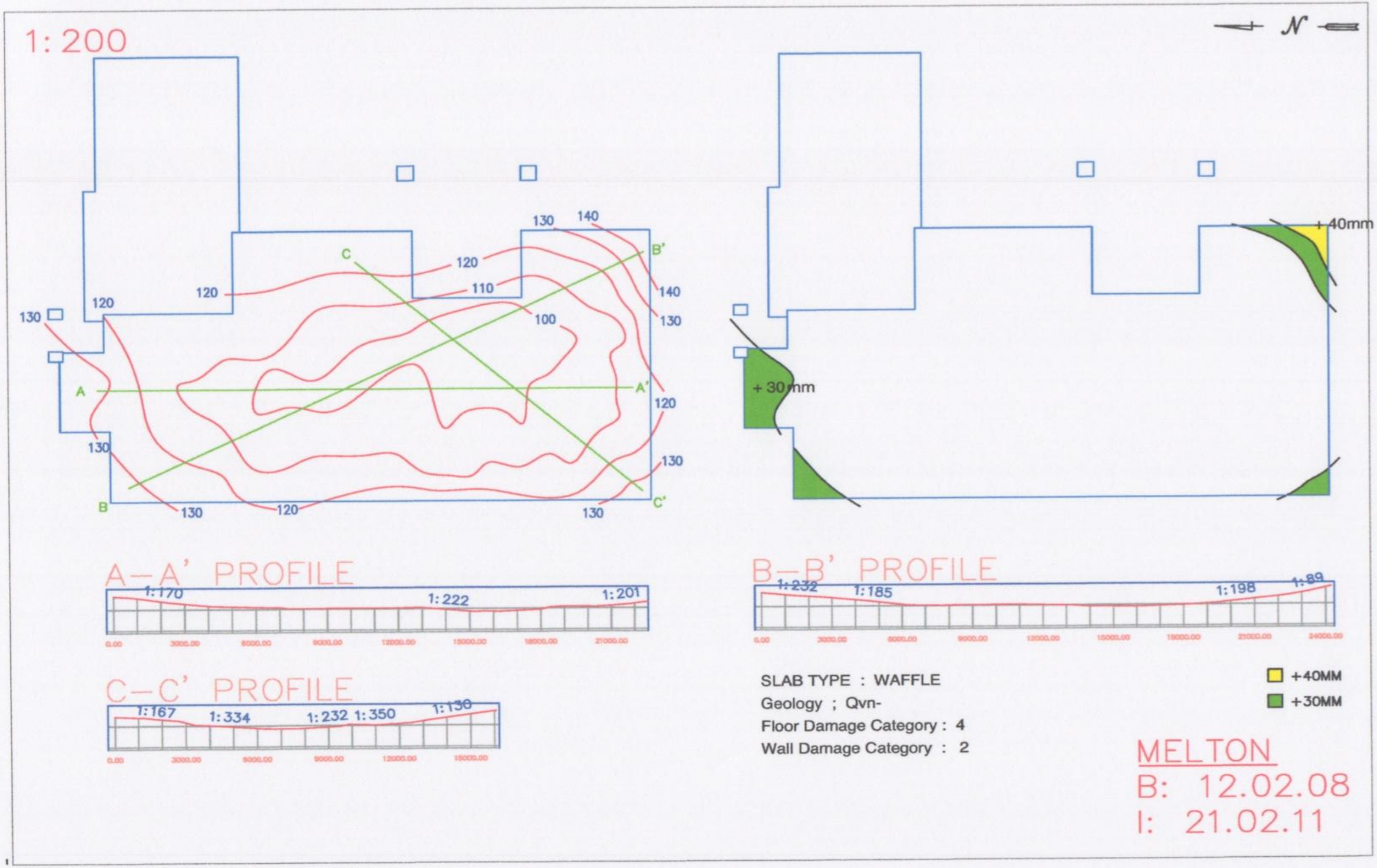


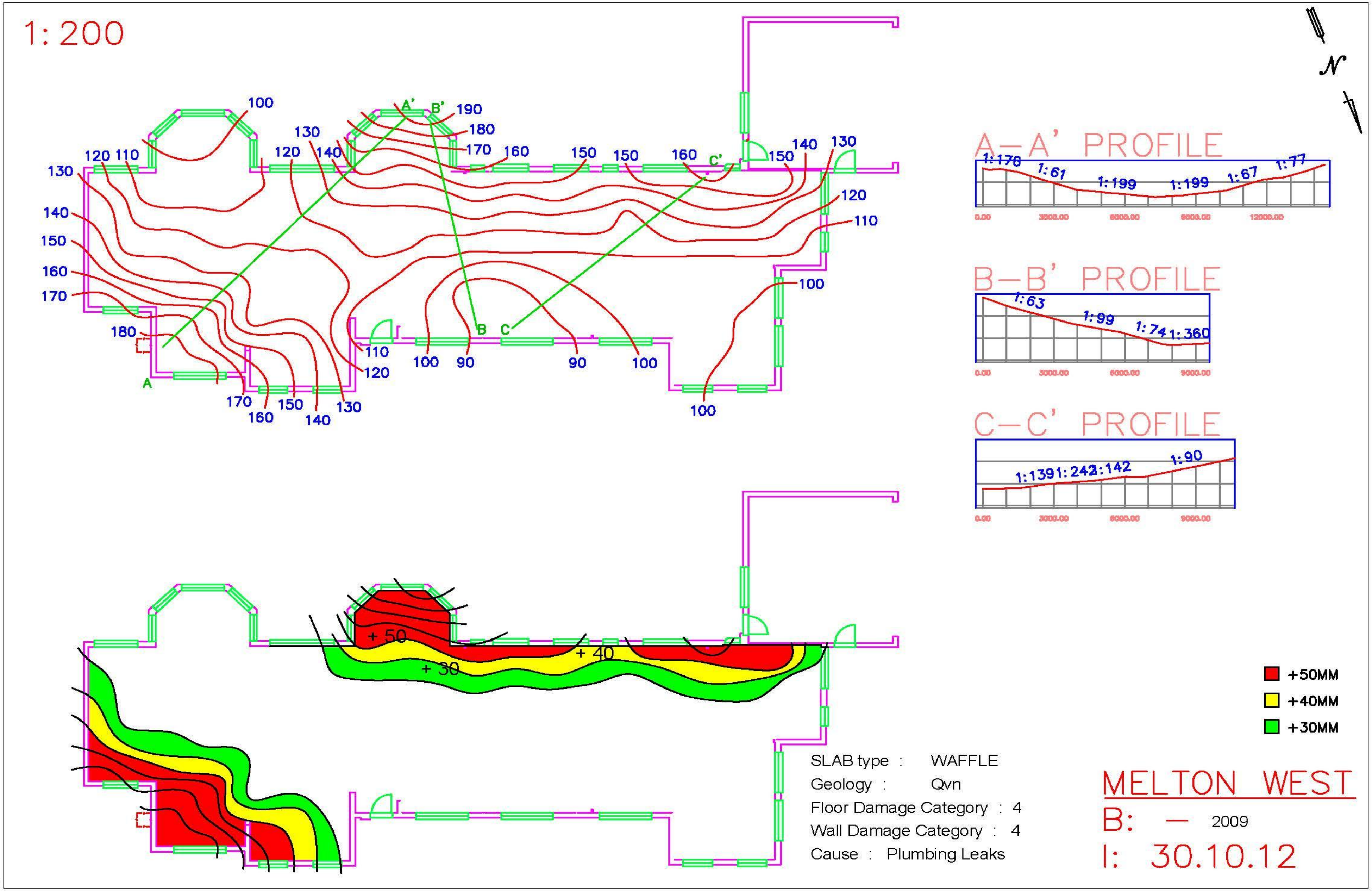
SLAB TYPE ; WAFFLE
Geology : Qvn
Floor Damage category : 3
Wall Damage Category : 2
Cause of Movement : Plumbing leaks

MELTON
B: 30.09.00
I: 27.11.09

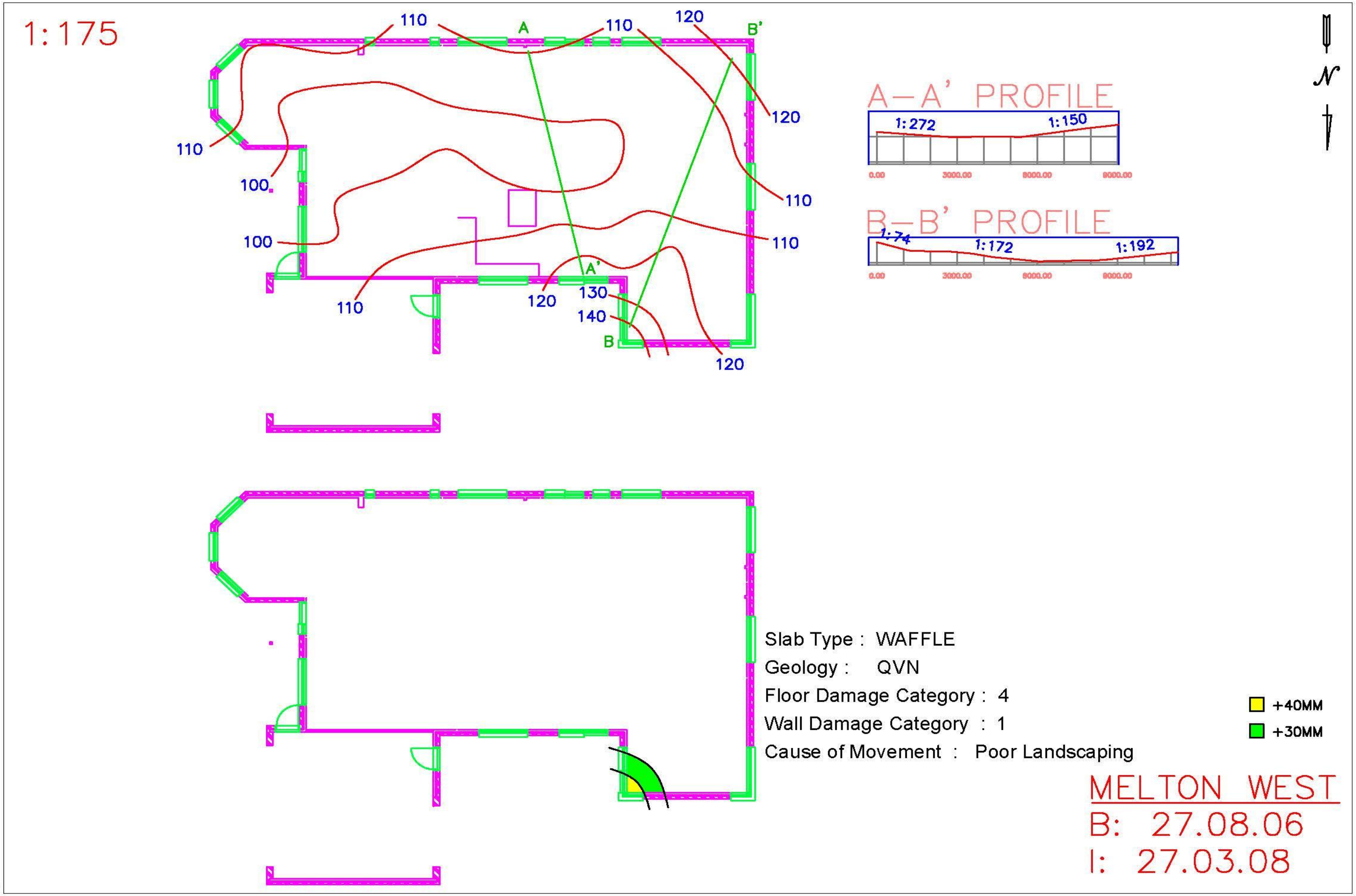

1: 200
A
B
B'
C
C'
A'
150
140
130
120
110
100
A—A' PROFILE
1: 141
1: 132
B—B' PROFILE
1: 239
1: 107
1: 234
1: 149
C—C' PROFILE
1: 147
1: 336
1: 97
1: 293
0.00
3000.00
6000.00
9000.00
12000.00
+ 50
+ 40
+ 30
+50MM
+40MM
+30MM
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 4
Wall Damage Category : 2
Cause of Movement : Poor Site Drainage.
MELTON
B: —
I: 08.04.13

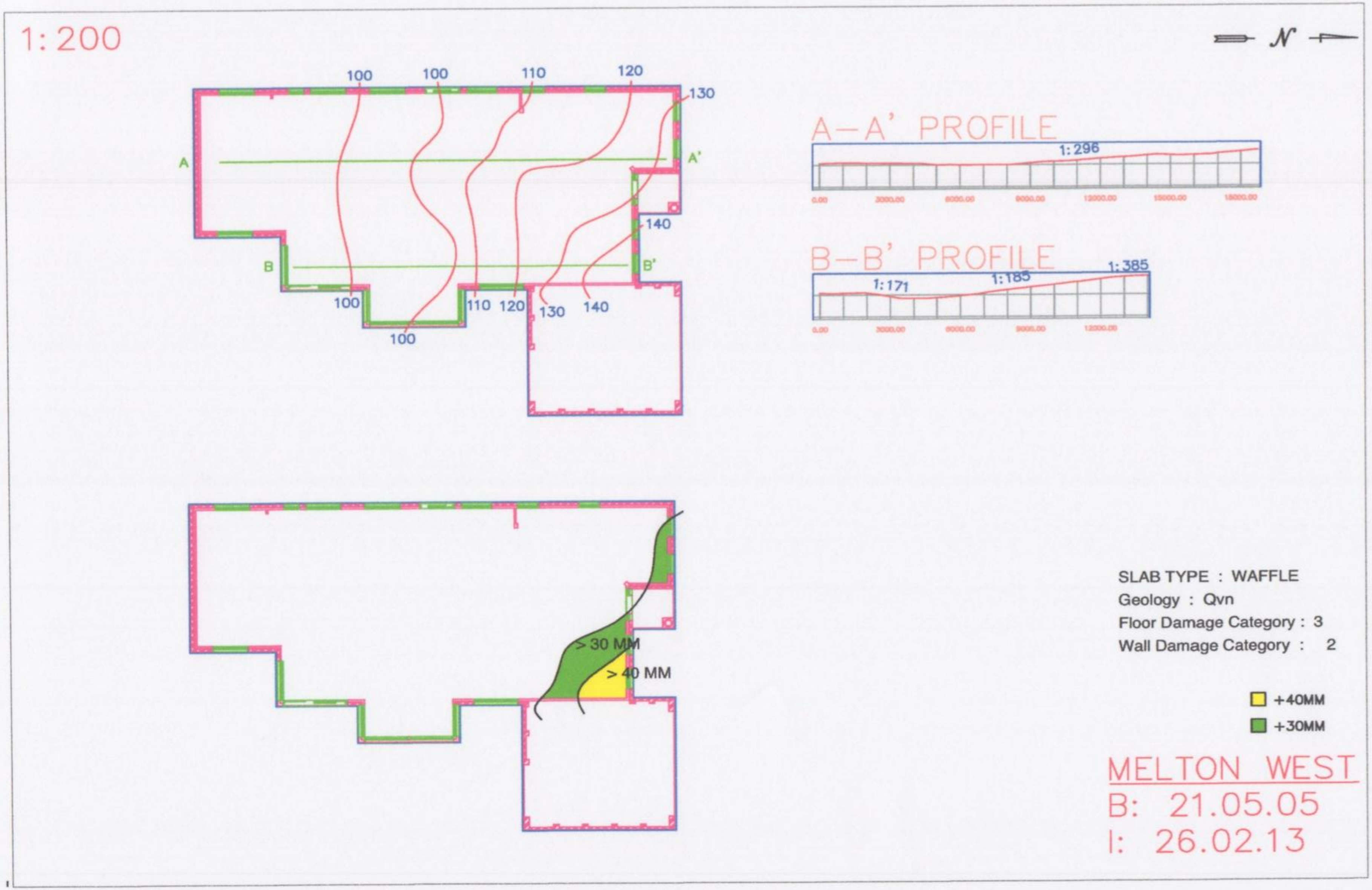

1: 200
A–A' PROFILE
1:351
1:166
1:185
1:313
1:211
B–B' PROFILE
1:107
1:375
1:393
1:216
C–C' PROFILE
1:177
1:264
+ 40
+ 30
+40MM
+30MM
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 3
Cause of Movement : Poor site drainage.
MELTON
B: 28.07.07
I: 11.10.12

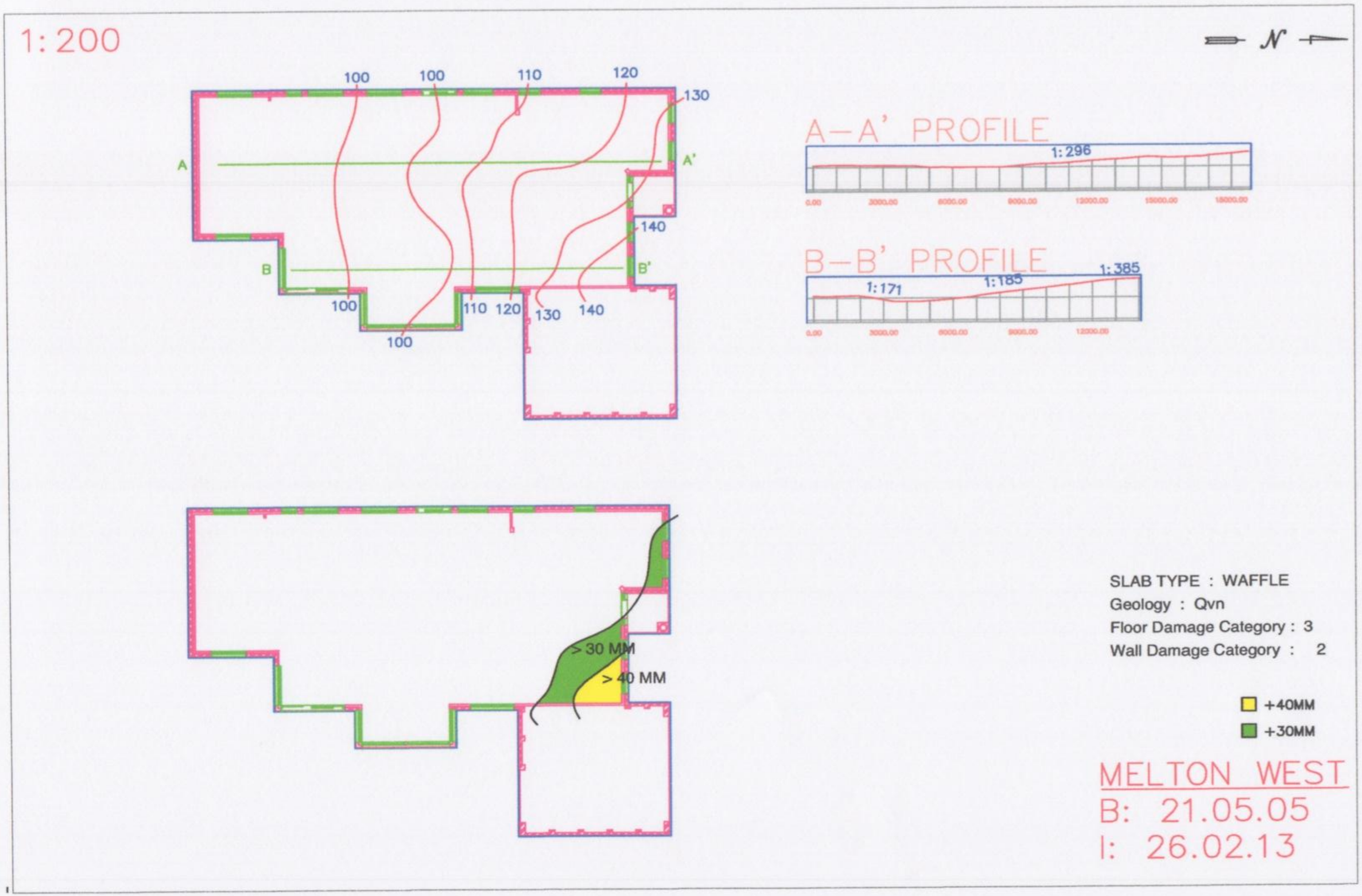

1: 200
130
140
C
B'
120
110
100
120
120
130
140
130
A
A'
120
130
130
B
130
120
130
C'
+40mm
+ 30 mm
A–A' PROFILE
1:170
1:222
1:201
B–B' PROFILE
1:232
1:185
1:198
1:89
C–C' PROFILE
1:167
1:334
1:232
1:350
1:130
SLAB TYPE : WAFFLE
Geology ; Qvn-
Floor Damage Category : 4
Wall Damage Category : 2
+40MM
+30MM
MELTON
B: 12.02.08
I: 21.02.11

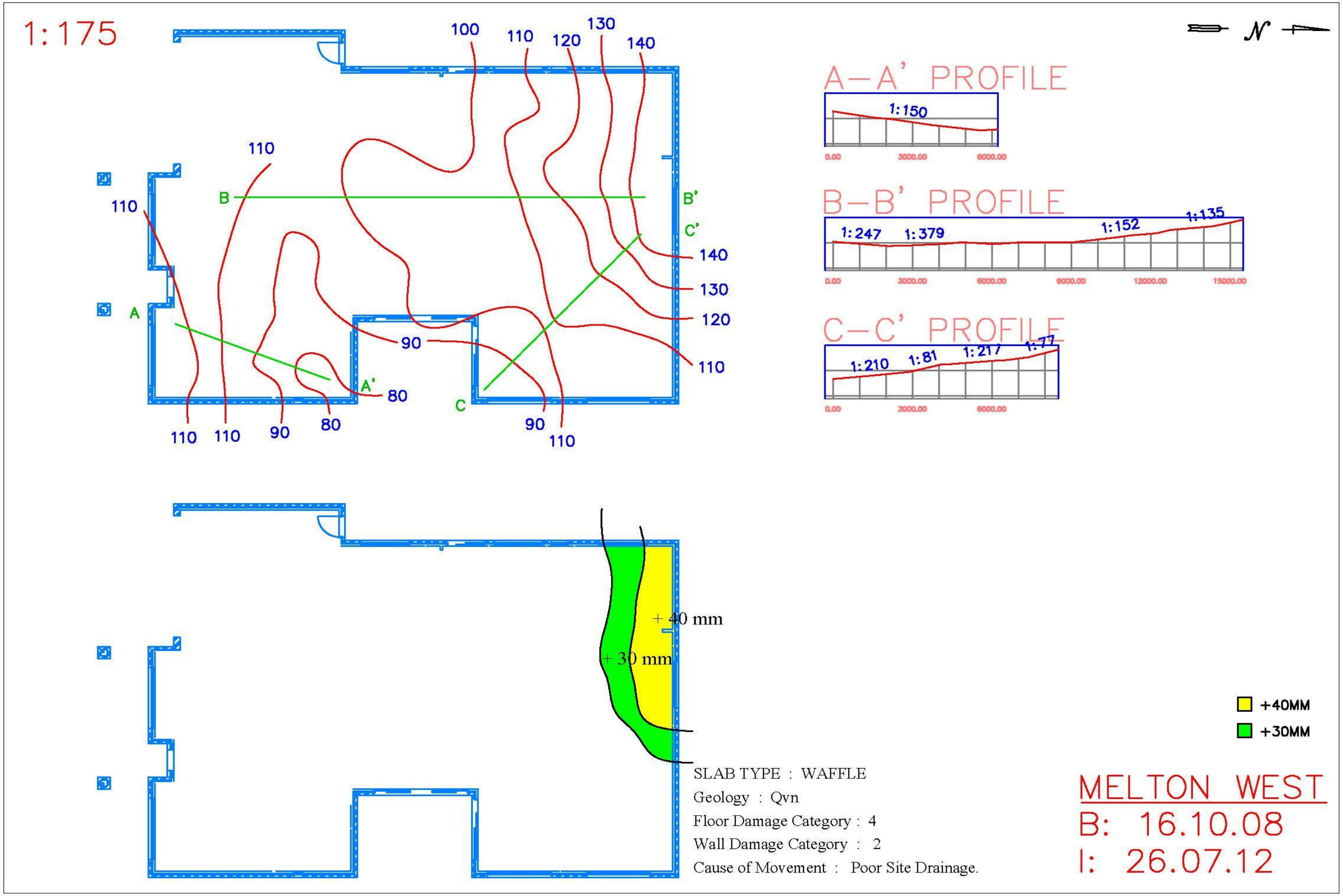


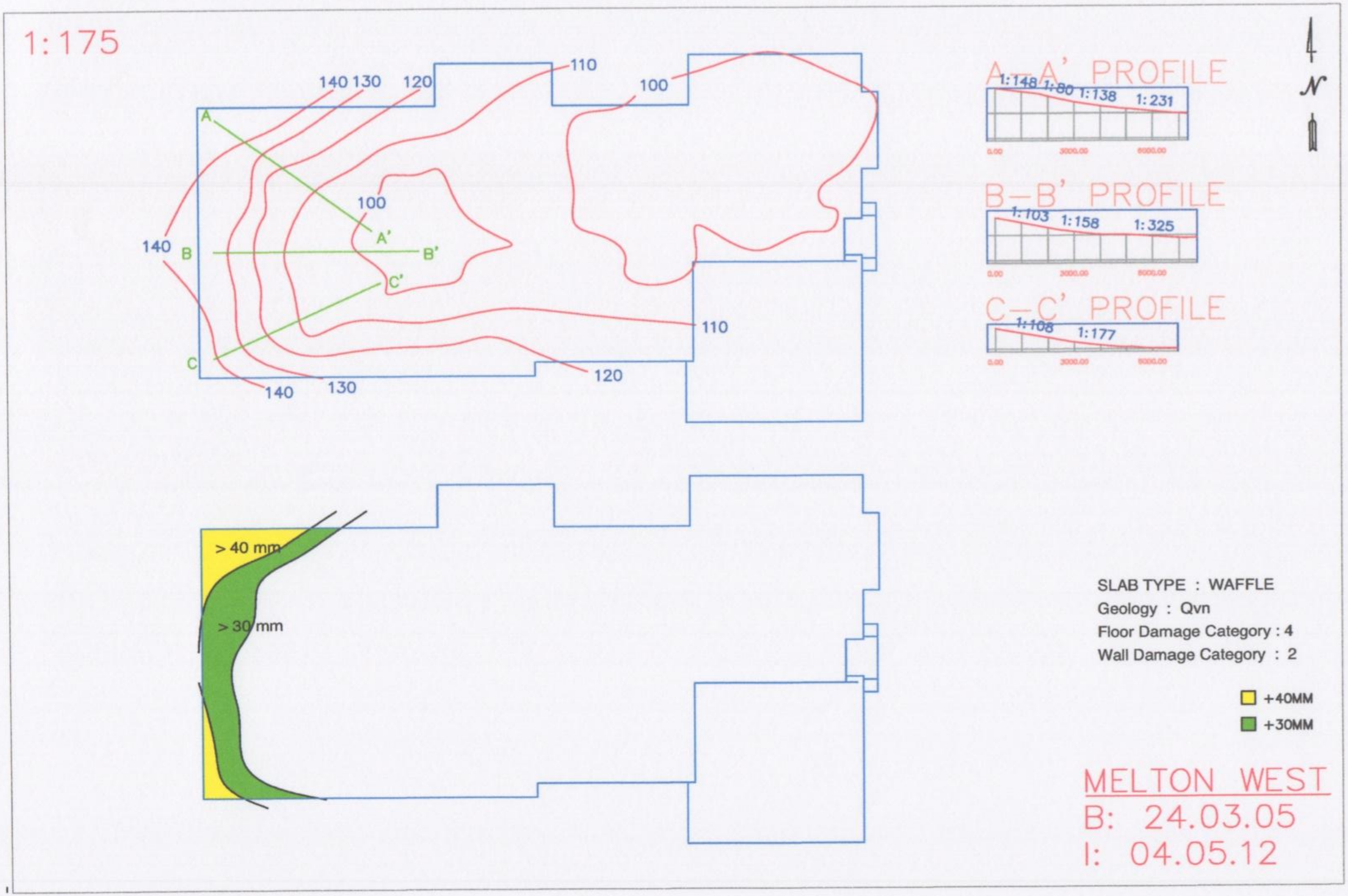
1: 200
A—A' PROFILE
1:176 1:61 1:199 1:199 1:67 1:77
B—B' PROFILE
1:63 1:99 1:74 1:360
C—C' PROFILE
1:139 1:242 1:142 1:90
+50MM
+40MM
+30MM
SLAB type : WAFFLE
Geology : Qvn
Floor Damage Category : 4
Wall Damage Category : 4
Cause : Plumbing Leaks
MELTON WEST
B: — 2009
I: 30.10.12

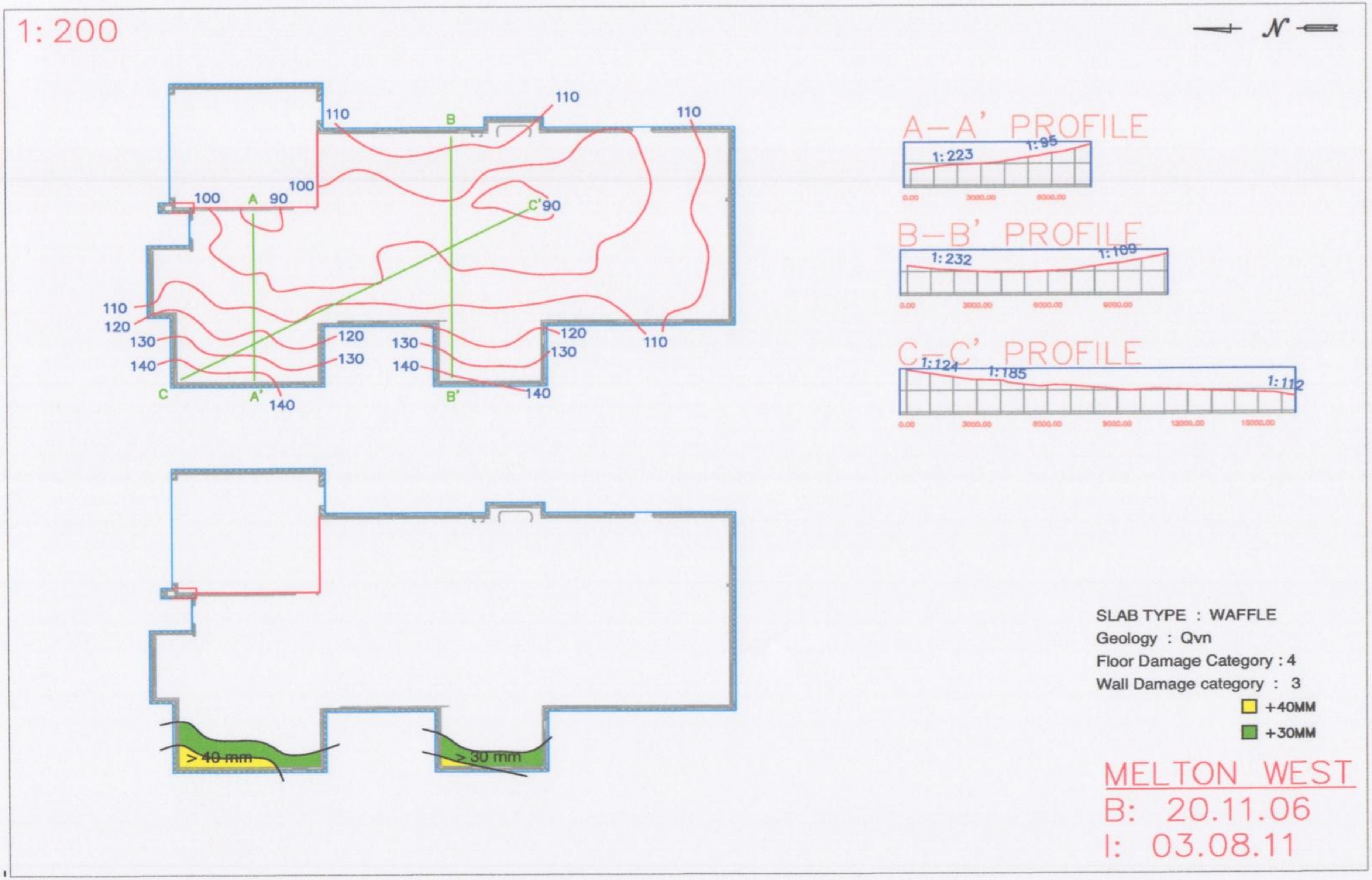

1:175
110
A
110
120
B'
120
110
100
100
110
110
A'
120
130
140
B
120
110
A–A' PROFILE
1:272
1:150
B–B' PROFILE
1:74
1:172
1:192
N
Slab Type : WAFFLE
Geology : QVN
Floor Damage Category : 4
Wall Damage Category : 1
Cause of Movement : Poor Landscaping
+40MM
+30MM
MELTON WEST
B: 27.08.06
I: 27.03.08


1: 200
N
100
100
110
120
130
A
A'
140
B
B'
100
110
120
130
140
100
A–A' PROFILE
1: 296
B–B' PROFILE
1: 171
1: 185
1: 385
> 30 MM
> 40 MM
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 2
+40MM
+30MM
MELTON WEST
B: 21.05.05
I: 26.02.13

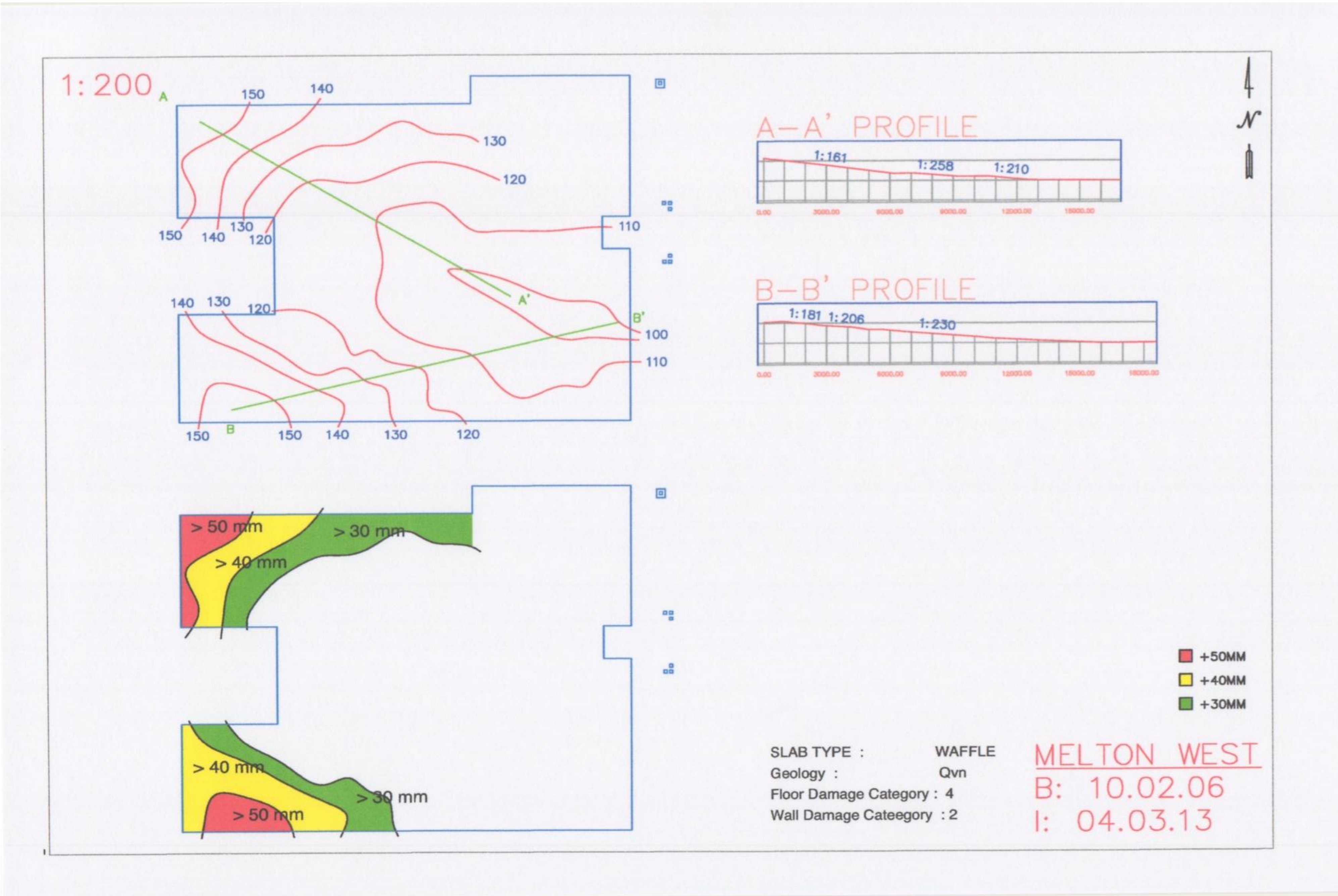

1: 200
N
100
100
110
120
130
A
A'
140
B
B'
100
110
120
130
140
100
A—A' PROFILE
1: 296
B—B' PROFILE
1: 171
1: 185
1: 385
> 30 MM
> 40 MM
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 2
+40MM
+30MM
MELTON WEST
B: 21.05.05
I: 26.02.13

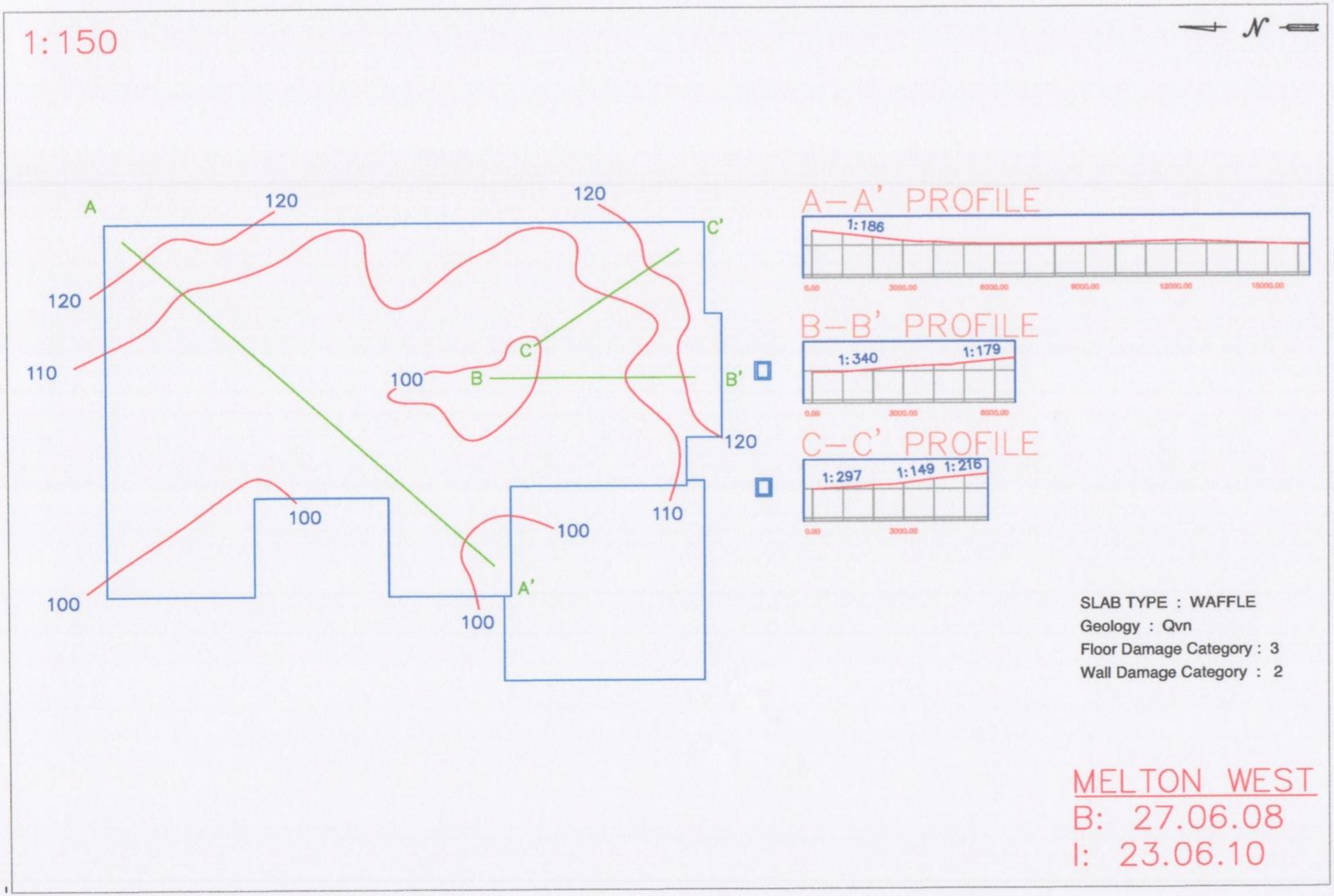

1:175
N
100
110
120
130
140
110
110
B
B'
C'
140
130
120
110
A
A'
90
80
C
90
110
110
110
90
80
A–A' PROFILE
1:150
B–B' PROFILE
1:247
1:379
1:152
1:135
C–C' PROFILE
1:210
1:81
1:217
1:77
+ 40 mm
+ 30 mm
+40MM
+30MM
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 4
Wall Damage Category : 2
Cause of Movement : Poor Site Drainage.
MELTON WEST
B: 16.10.08
I: 26.07.12

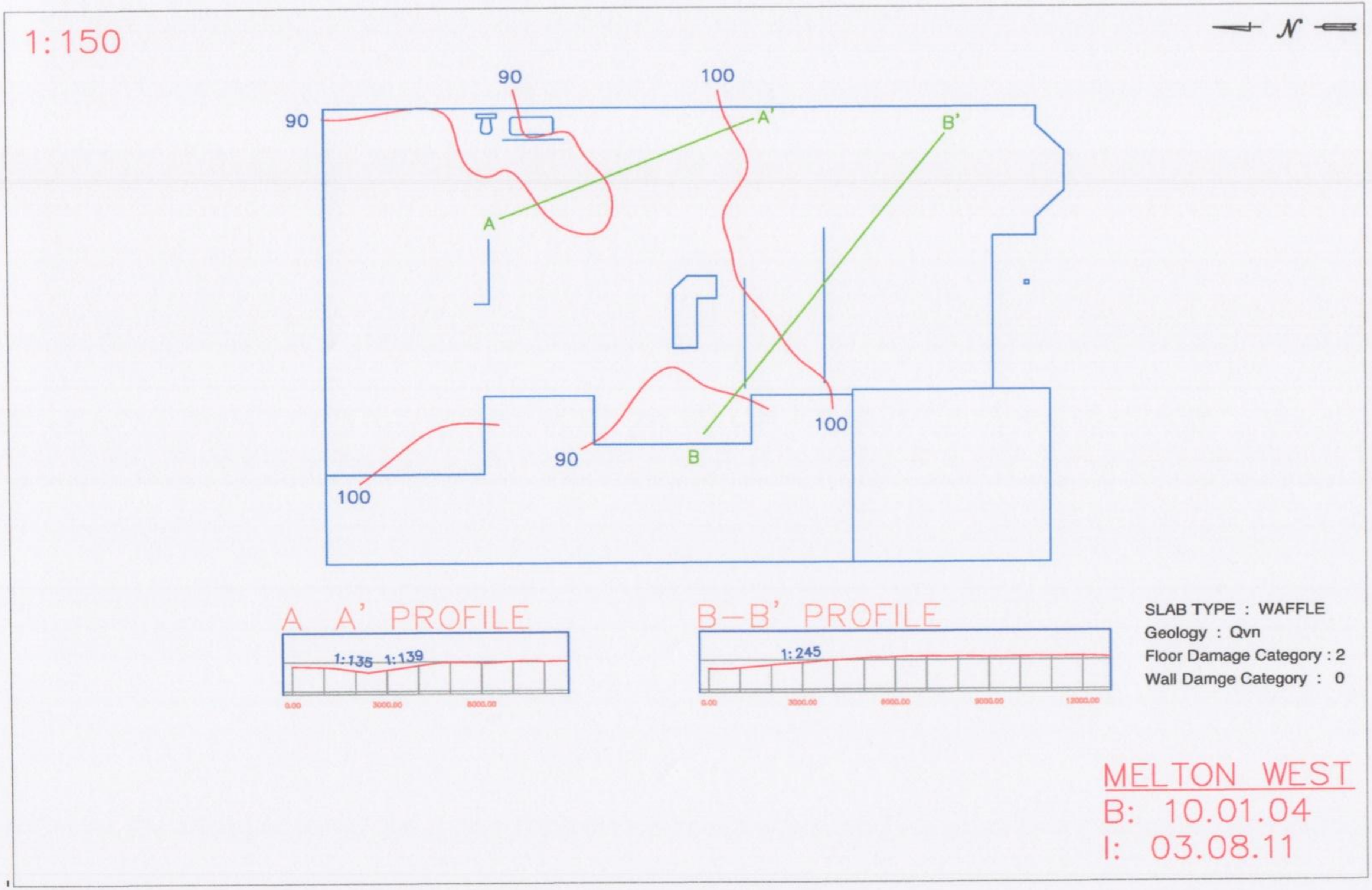

1:175
140 130
120
110
100
A
100
A'
140
B
B'
C'
110
C
120
140
130
A—A' PROFILE
1:148
1:80
1:138
1:231
B—B' PROFILE
1:103
1:158
1:325
C—C' PROFILE
1:108
1:177
N
> 40 mm
> 30 mm
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 4
Wall Damage Category : 2
+40MM
+30MM
MELTON WEST
B: 24.03.05
I: 04.05.12

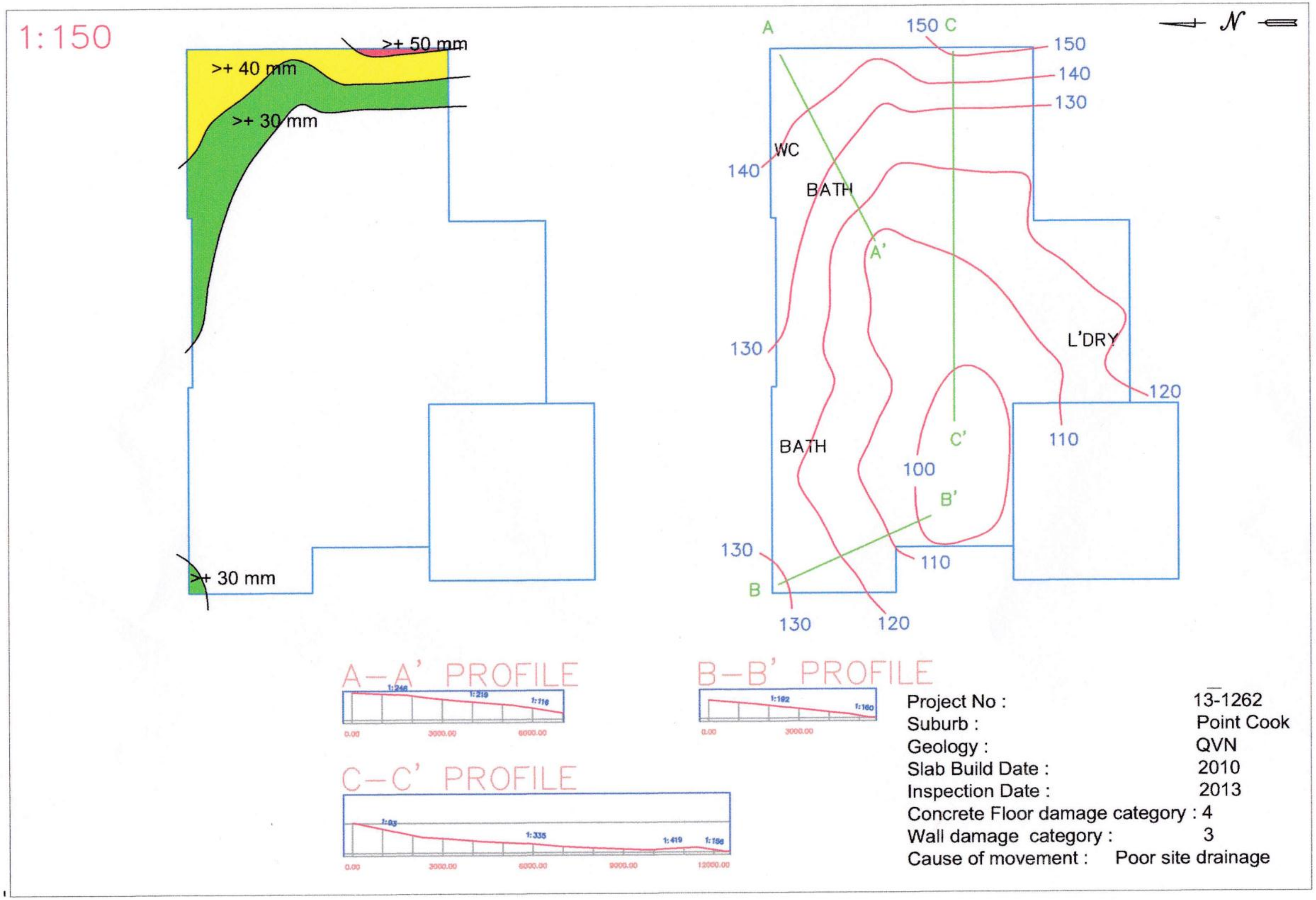


1: 200
N
110
110
110
B
100
100
A
90
C'
90
110
120
130
140
C
A'
140
120
130
130
140
B'
140
120
130
110
A–A' PROFILE
1: 223
1: 95
B–B' PROFILE
1: 232
1: 109
C–C' PROFILE
1: 124
1: 185
1: 112
> 40 mm
> 30 mm
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 4
Wall Damage category : 3
+40MM
+30MM
MELTON WEST
B: 20.11.06
I: 03.08.11

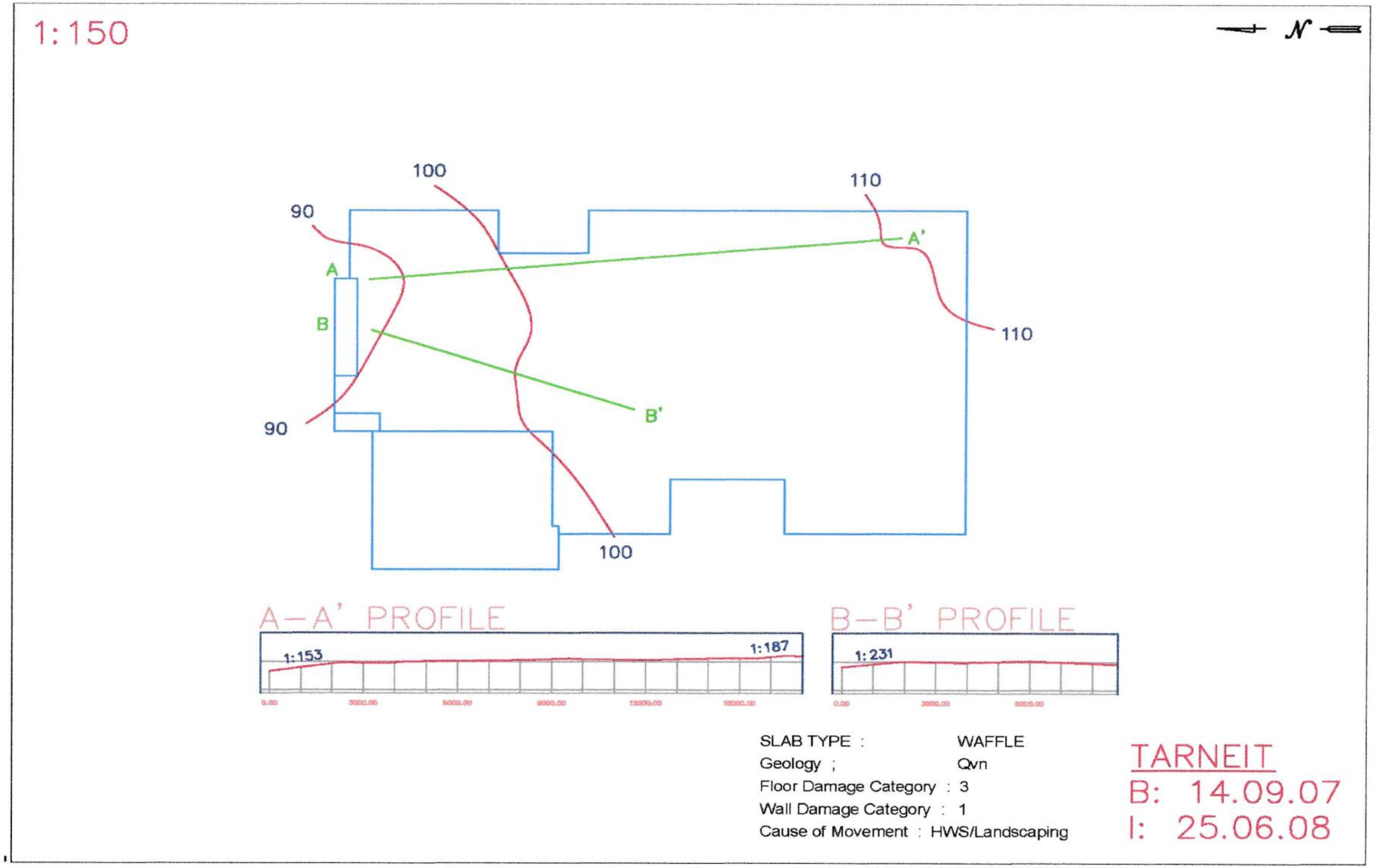

1: 200
A
150
140
130
120
110
100
110
150 140 130 120
140 130 120
A'
B'
B
150 B 150 140 130 120
A–A' PROFILE
1:161
1:258
1:210
B–B' PROFILE
1:181 1:206
1:230
N
> 50 mm
> 40 mm
> 30 mm
> 40 mm
> 30 mm
> 50 mm
+50MM
+40MM
+30MM
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 4
Wall Damage Cateegory : 2
MELTON WEST
B: 10.02.06
I: 04.03.13

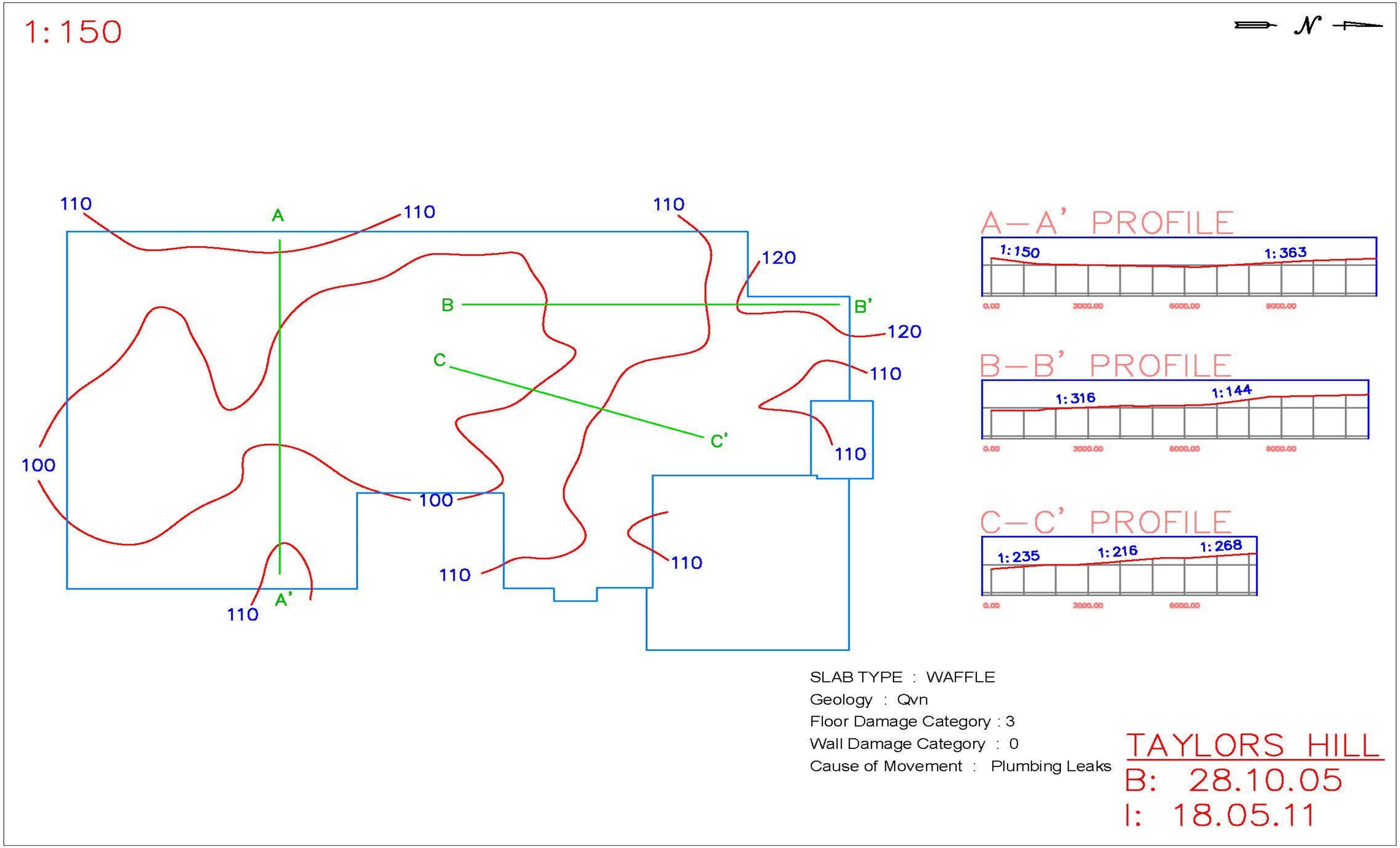

1:150
A
A'
B
B'
C
C'
120
120
120
120
110
110
100
100
100
100
100
100
A–A' PROFILE
1:186
B–B' PROFILE
1:340
1:179
C–C' PROFILE
1:297
1:149
1:216
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 2
MELTON WEST
B: 27.06.08
I: 23.06.10

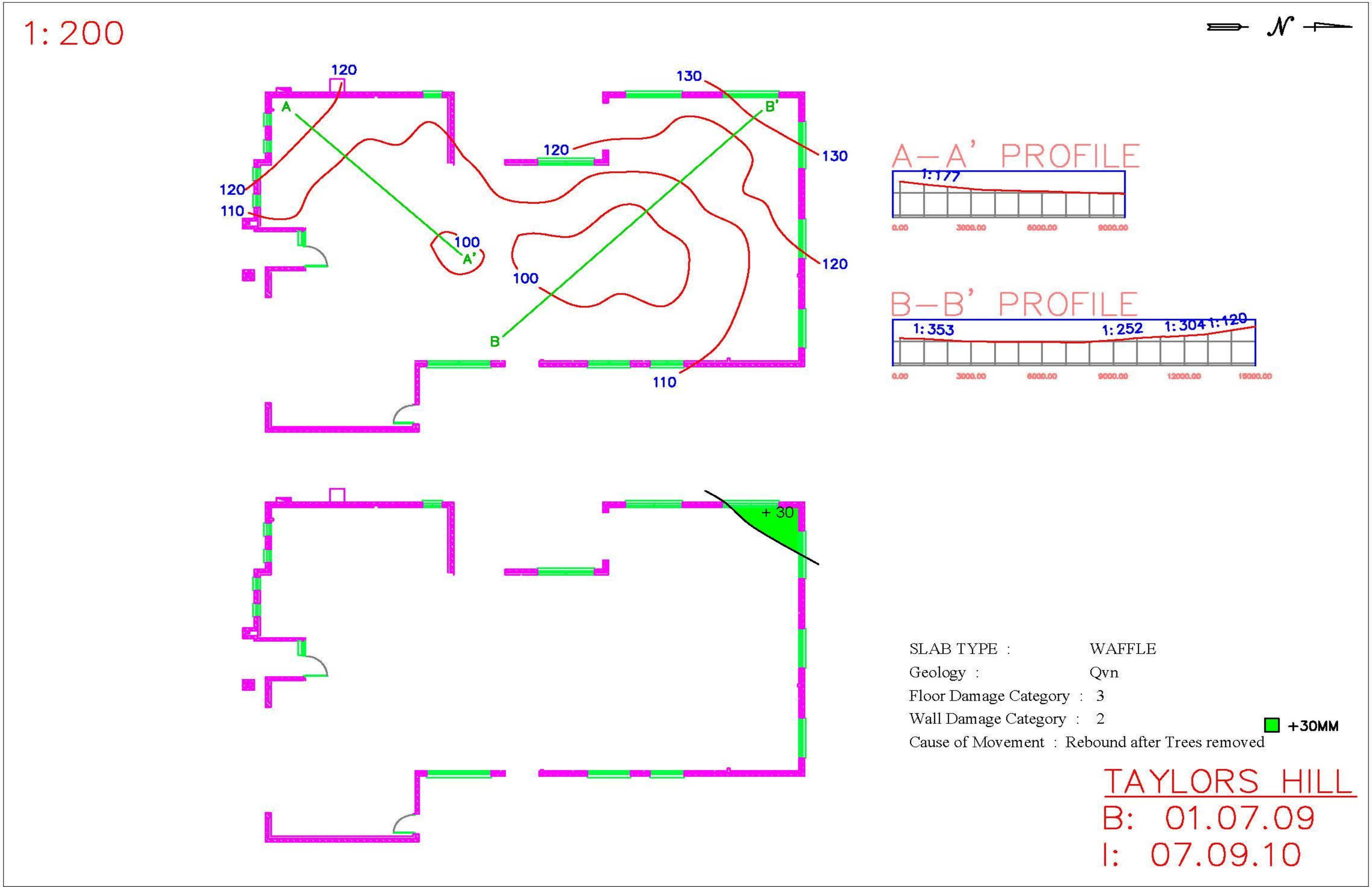

1:150
90
100
90
A
A'
B'
100
90
B
100
A A' PROFILE
1:135 1:139
B–B' PROFILE
1:245
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 2
Wall Damge Category : 0
MELTON WEST
B: 10.01.04
I: 03.08.11

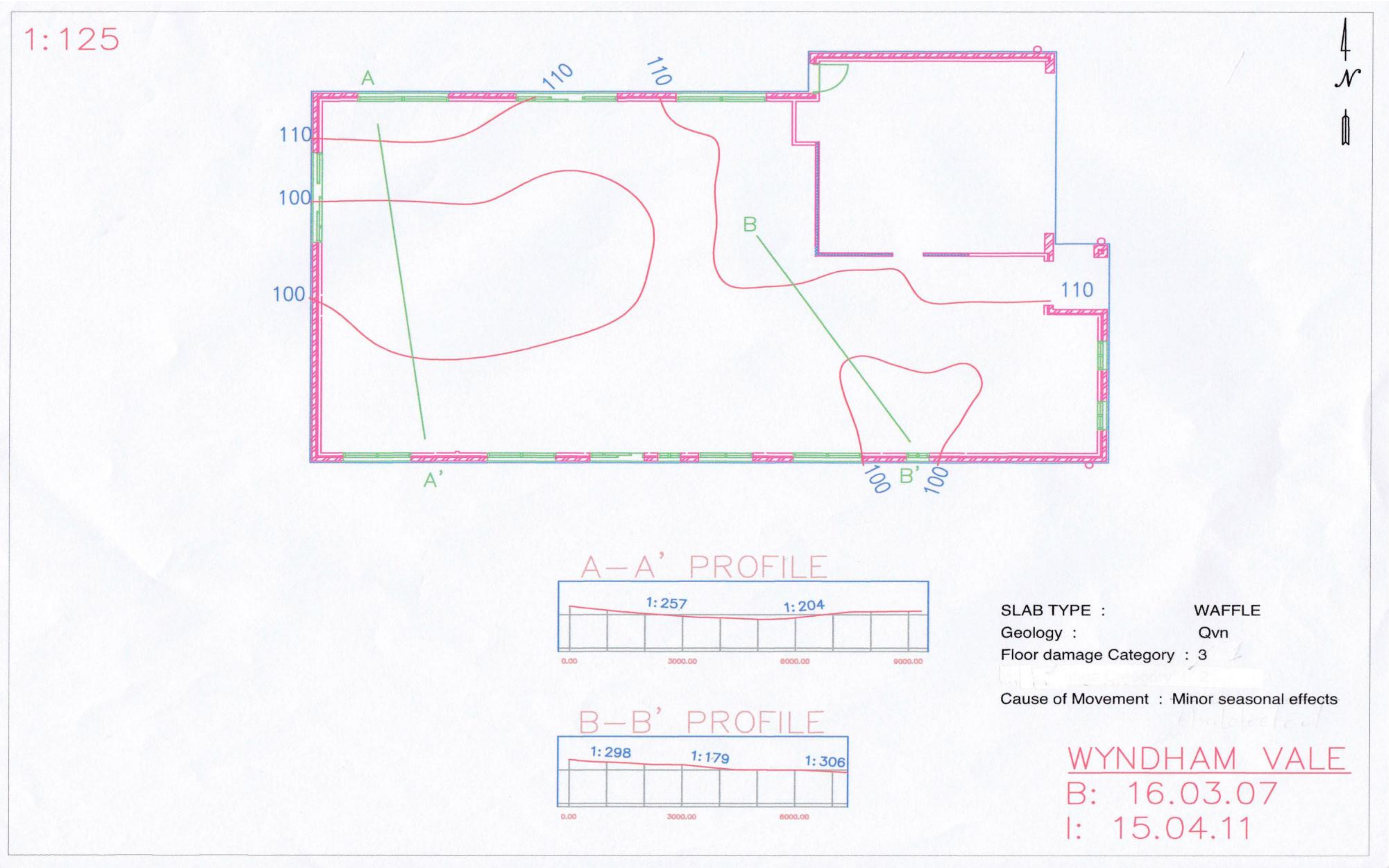


Project No :	13-1262
Suburb :	Point Cook
Geology :	QVN
Slab Build Date :	2010
Inspection Date :	2013
Concrete Floor damage category :	4
Wall damage category :	3
Cause of movement :	Poor site drainage


1:150
N
90
100
110
A
A'
B
B'
90
100
110
A–A' PROFILE
1:153
1:187
B–B' PROFILE
1:231
SLAB TYPE : WAFFLE
Geology ; Qvn
Floor Damage Category : 3
Wall Damage Category : 1
Cause of Movement : HWS/Landscaping
TARNEIT
B: 14.09.07
I: 25.06.08


1:150
N
110
A
110
110
120
B
B'
120
C
110
C'
110
100
100
110
110
A'
110
A–A' PROFILE
1:150
1:363
0.00
3000.00
6000.00
B–B' PROFILE
1:316
1:144
0.00
3000.00
6000.00
C–C' PROFILE
1:235
1:216
1:268
0.00
3000.00
6000.00
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 0
Cause of Movement : Plumbing Leaks
TAYLORS HILL
B: 28.10.05
I: 18.05.11


1: 200
120
130
120
130
120
110
100
A
A'
B
B'
100
120
110
+ 30
A–A' PROFILE
1:177
B–B' PROFILE
1:353
1:252
1:304
1:120
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 3
Wall Damage Category : 2
Cause of Movement : Rebound after Trees removed
+30MM
TAYLORS HILL
B: 01.07.09
I: 07.09.10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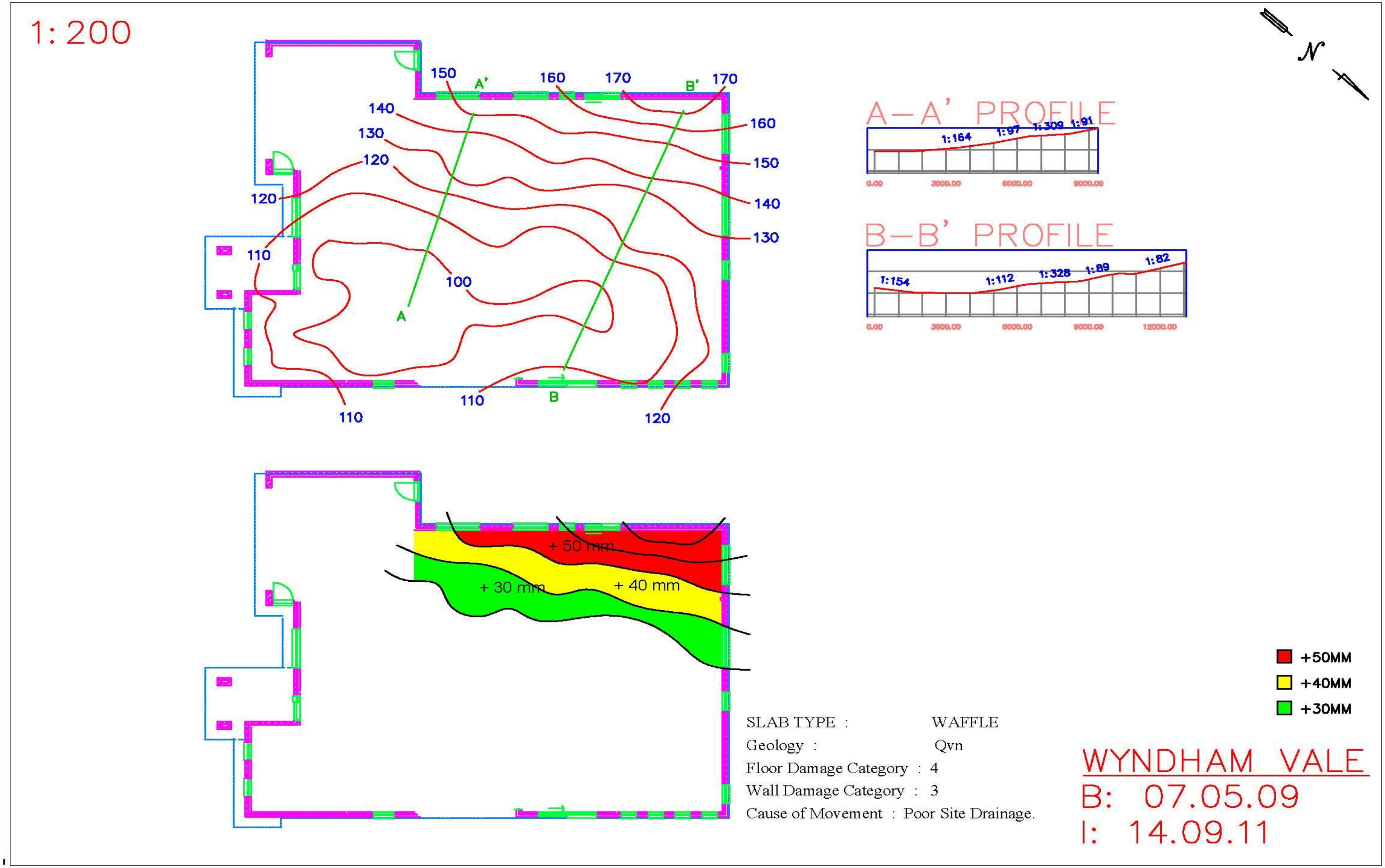
N
A
A'
B
B'
110
110
110
100
100
110
100
100
A—A' PROFILE
1:257
1:204
0.00
3000.00
6000.00
9000.00
B—B' PROFILE
1:298
1:179
1:306
0.00
3000.00
6000.00
SLAB TYPE : WAFFLE
Geology : Qvn
Floor damage Category : 3
Cause of Movement : Minor seasonal effects
WYNDHAM VALE
B: 16.03.07
I: 15.04.11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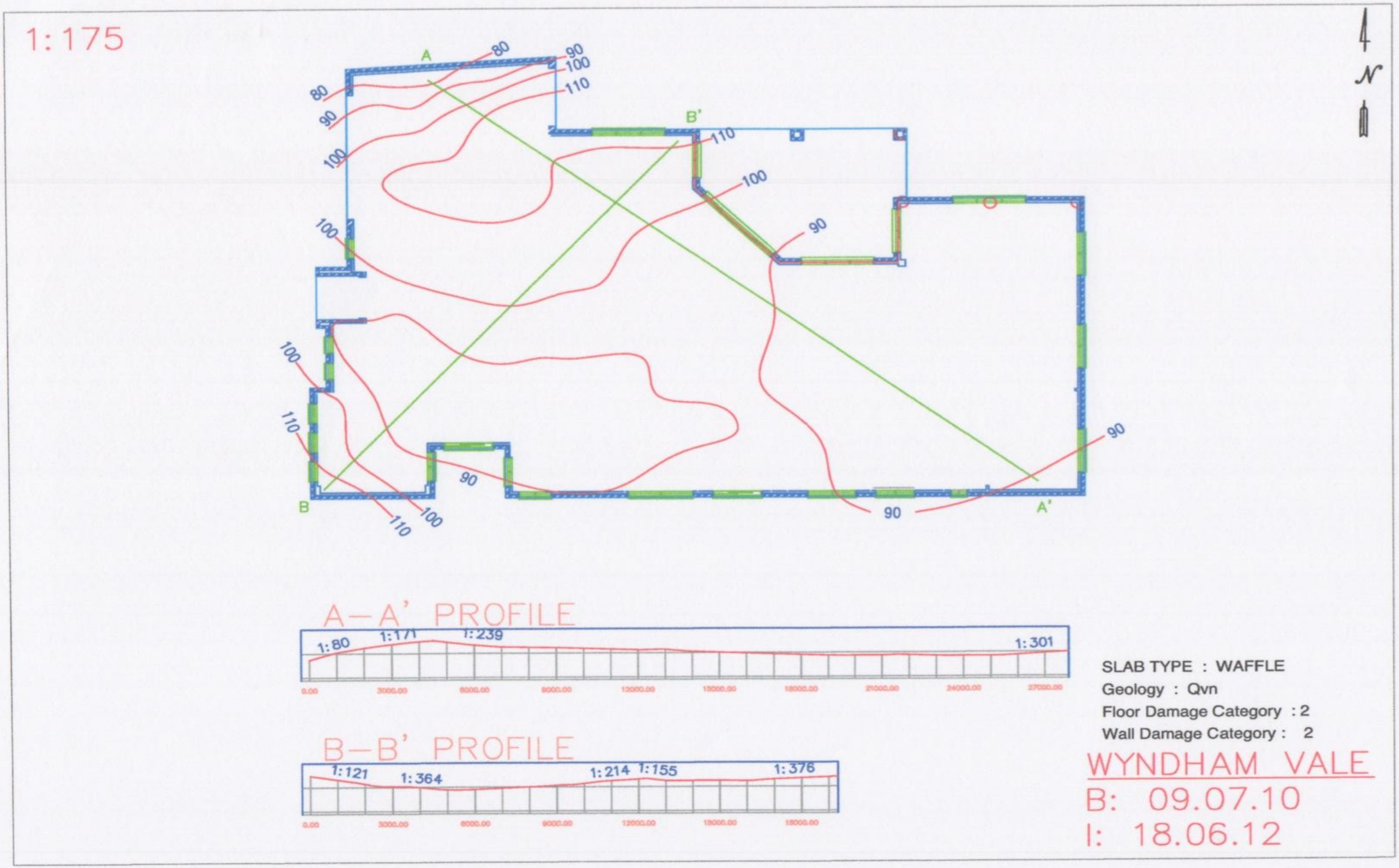
N
150
A'
160
170
B'
170
140
160
130
150
120
140
120
130
110
100
A
110
B
120
110
A—A' PROFILE
1:164
1:97
1:309
1:91
0.00
3000.00
6000.00
9000.00
B—B' PROFILE
1:154
1:112
1:328
1:89
1:82
0.00
3000.00
6000.00
9000.00
12000.00
+ 50 mm
+ 30 mm
+ 40 mm
+50MM
+40MM
+30MM
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 4
Wall Damage Category : 3
Cause of Movement : Poor Site Drainage.
WYNDHAM VALE
B: 07.05.09
I: 14.09.11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A
B'
B
A'
80
90
100
110
A—A' PROFILE
1:80
1:171
1:239
1:301
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3000.00
6000.00
9000.00
12000.00
15000.00
18000.00
21000.00
24000.00
27000.00
B—B' PROFILE
1:121
1:364
1:214
1:155
1:376
SLAB TYPE : WAFFLE
Geology : Qvn
Floor Damage Category : 2
Wall Damage Category : 2
WYNDHAM VALE
B: 09.07.10
I: 18.06.12

APPENDIX 2

SLAB CONTOURS, MEASURED DIFFERENTIAL LEVELS & SLAB DAMAGE CATEGORIES (42 S-O-G)

Classification of damage categories of concrete floors and walls is used by AS2870 as a reasonable performance expectation. The wall damage categories are not quoted here since in many cases the walls had already been repaired at least once. Floor damage category 2 is considered 'slight', 3 moderate, 4 severe. An overall deviation of slope in excess of 1:150 is considered undesirable per AS2870 and the maximum design slope is 1:400. Each contour plan notes the Geology, built date, test date (English style) and suburb; however, due to privacy issues, the street and house numbers have been omitted. The full address is recorded in the investigation files. All of the houses were built during the Millennium drought; 4 were investigated during this drought and 38 after the breaking of the drought. Of the 42 houses 24 had a differential slab distortions ≤30 mm. The investigations were part of the scheduled maintenance by large builders and is considered as an example of the response by the builders to the concerns of the home owners during this time.

Houses supported by footing systems designed and constructed in accordance with this standard on a 'Normal' site that are not subject to abnormal moisture conditions; and maintained such as the **original site classification remains valid are expected to experience usually no damage, a low incidence of damage category 1 and an occasional incidence of category 2.**

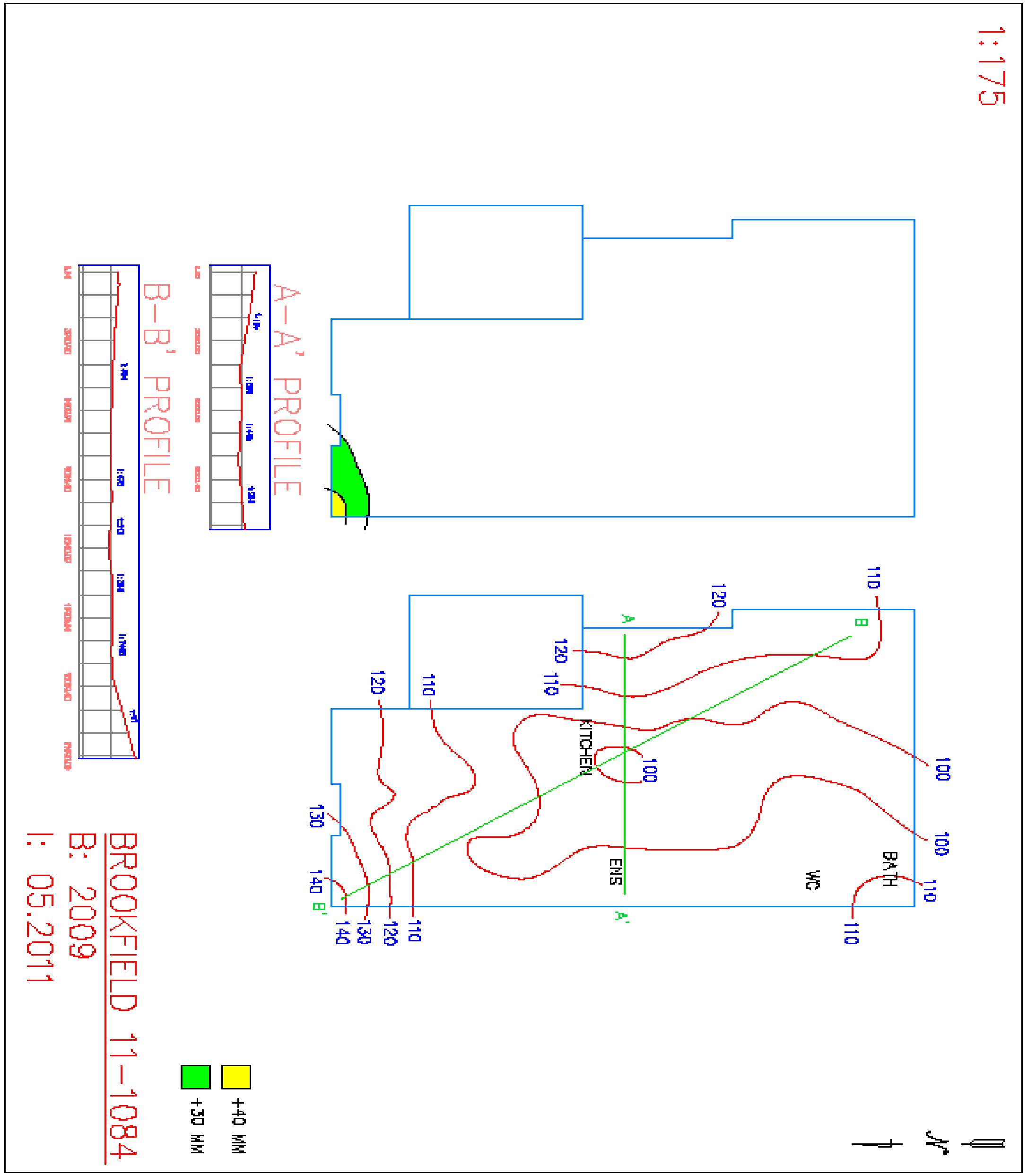
Location	Worst-case slab differential levels (mm)	Worst-case measured deflection as a function of 3 m span. (AS 2870 design 1/400)	Worst case damage (AS2870)	Comments	Cause
Brookfield	**40**	**1:91**	**4**	**Edge and front corner-lift.**	**Poor site drainage.**
Cairnlea (1)	**30**	**1:154**	**2**	**Slight SE corner-lift.**	**Seasonal effect.**
Cairnlea (2)	**50**	**1:97**	**4**	**South corner lift.**	**Seasonal effect.**
Caroline Springs (1)	**30**	**1:479**	**1**	**Very minor differential levels.**	**Undetected.**
Caroline Springs (2)	**30**	**1:195**	**2**	**Minor slab distortions.**	**Seasonal effects.**
Caroline Springs (3)	**10**	**1:340**	**1**	**V. minor slab distortion**	**Undetected**
Craigieburn	**20**	**1:108**	**3**	**Edge shrinkage settlement.**	**Tree drying/Drought drying.**

Deer Park	**30**	**1:164**	**3**	**Front corner lift**	**Pipe leak.**
Hillside (1)	**30**	**1:197**	**3**	**Rear slab lift.**	**Poor site drainage.**
Hillside (2)	**40**	**1:139**	**4**	**Slab lift on Sth side**	**Plumbing leaks.**
Hoppers Crossing	**30**	**1:157**	**3**	**South west corner shrinking.**	**Tree drying.**
Keilor Downs	**70**	**1:118**	**4**	**Water under slab, centre lift**	**Plumbing leak under kitchen.**
Keilor East	**70**	**1:100**	**4**	**Rear 2/3 slab lift**	**Poor site drainage**
Maidstone	**30**	**1:92**	**3**	**Rear half slab lift.**	**Poor site drainage.**
Melton	**30**	**1:76**	**3**	**Perimeter lift.**	**Poor site drainage.**
Melton West (1)	**30**	**1:82**	**3**	**Perimeter lift**	**Poor site drainage**
Melton West (2)	**40**	**1:97**	**3**	**Perimeter and corner lift**	**Poor landscaping**
Melton West (3)	**50**	**1:72**	**4**	**Perimeter slab lift**	**Poor site drainage**
Melton West (4)	**40**	**1:96**	**4**	**Perimeter lift**	**Poor site drainage**
Pt Cook (1)	**30**	**1:158**	**3**	**Rear slab lift**	**Leaky pipes/Poor site drainage.**
Pt Cook (2)	**20**	**1:78**	**3**	**Perimeter lift.**	**Flood after drought.**
Pt Cook (3)	**40**	**1:142**	**3**	**Lift on Sth side.**	**Flood after drought.**
Pt Cook (4)	**50**	**1:125**	**3**	**Lift on rear and perimeter.**	**Poor landscaping.**
Pt Cook (5)	**40**	**1:93**	**3**	**SE corner slab lift.**	**Leaky pipes.**
Pt Cook (6)	**50**	**1:64**	**4**	**Perimeter slab lift.**	**Poor site drainage.**
Pt Cook (7)	**50**	**1:83:**	**4**	**Perimeter slab lift**	**Poor site drainage**
St Albans	**70**	**1:65**	**4**	**Lift on front N.W. corner.**	**Plumbing leak.**
Sydenham	**50**	**1:130**	**3**	**Lift on 3 corners**	**Poor site drainage.**
Tarneit (1)	**20**	**1:191**	**2**	**Lift on 3 corners**	**Poor site drainage.**
Tarneit (2)	**20**	**1:71**	**3**	**Lift on 2 corners.**	**Poor site drainage/Pipe leaks**
Tarneit (3)	**30**	**1:120**	**2**	**Edge-lift on N.W. side.**	**Poor site drainage**
Tarneit (4)	**60**	**1:59**	**4**	**Perimeter slab lift.**	**Poor site drainage.**

Taylors Hill (1)	**20**	**1:157**	**2**	**Minor edge lift S. side.**	**Poor site drainage.**
Taylors Hill (2)	**60**	**1:72**	**3**	**Rear corner lift on East side.**	**Pipe leaks.**
Truganina (1)	**40**	**1:161**	**3**	**Rear corner lift.**	**Poor site drainage**
Truganina (2)	**40**	**1:71**	**4**	**Rear slab lift.**	**Poor site drainage.**
Truganina (3)	**50**	**1:61**	**4**	**Perimeter slab lift.**	**Poor drainage/pipe leak.**
Truganina (4)	**10**	**1:240**	**2**	**Minor SE corner shrink.**	**Drought drying.**
Werribee (1)	**50**	**1:97**	**4**	**Perimeter lift.**	**Poor site drainage/Pipe leaks.**
Werribee (2)	**30**	**1:319**	**2**	**Edge shrink.**	**Drought drying.**
Wyndham Vale (1)	**20**	**1:140**	**2**	**Minor perimeter lift.**	**Poor site drainage.**
Wyndham Vale (2)	**30**	**1:81**	**3**	**SW corner slab lift.**	**Poor site drainage.**

Causes of damage	Number affected	Percentage affected
Poor site drainage.	22	52%
Plumbing leaks.	10	24%
Seasonal effects.	3	7%
Drought drying effect	3	7%
Poor landscaping	2	5%
Flood after drought.	2	5%
Tree drying.	2	5%
Undetected.	2	5%

*** Number of houses with 2 distinct causes = 5.**
**** Damage could have been reduced if site classifications had considered a 'E' alternative as shown in AS2870 table D1.**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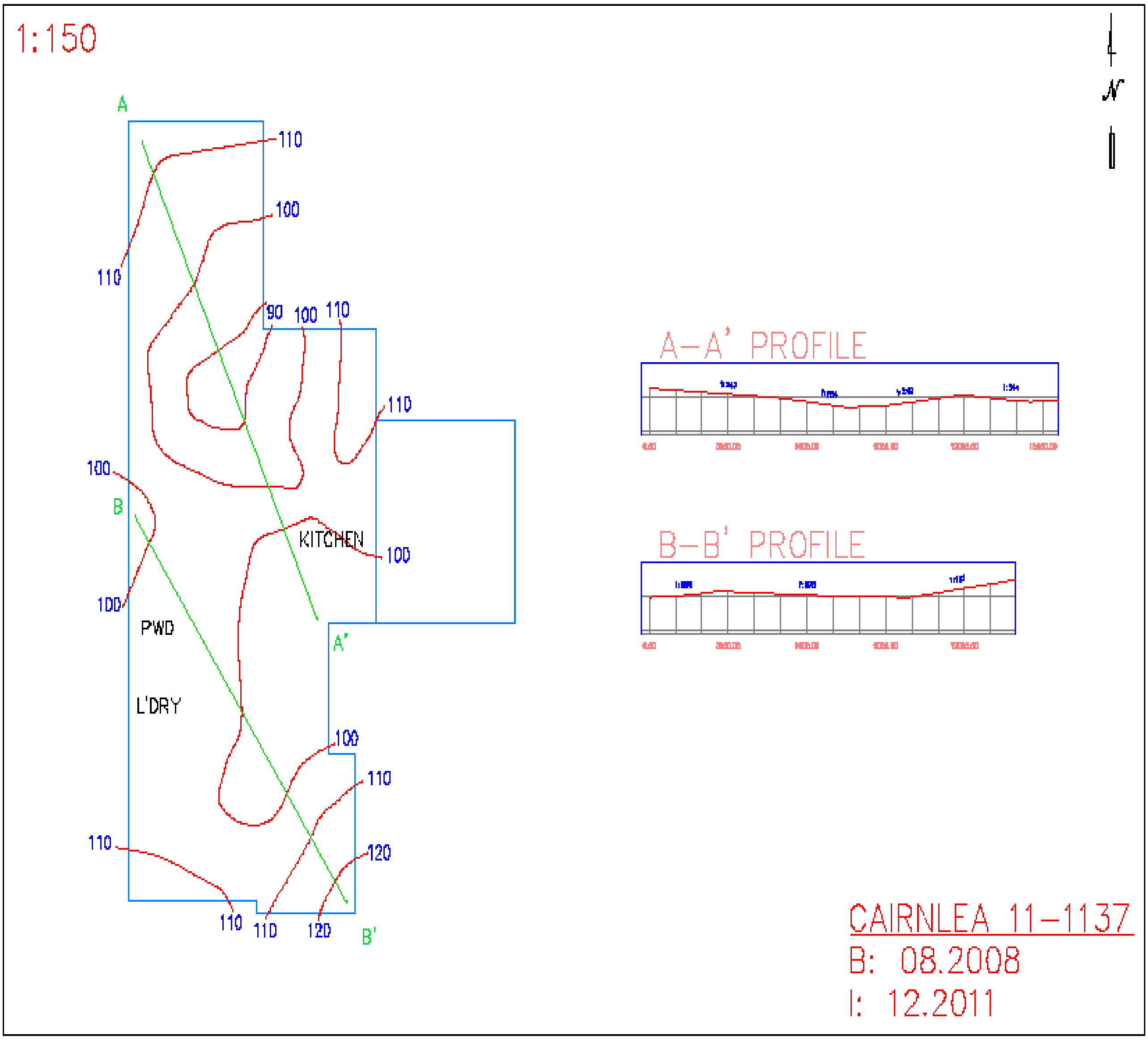
B-B' PROFILE
KITCHEN
ENS
WC
BATH
+40 MM
+30 MM
BROOKFIELD 11-1084
B: 2009
I: 05.2011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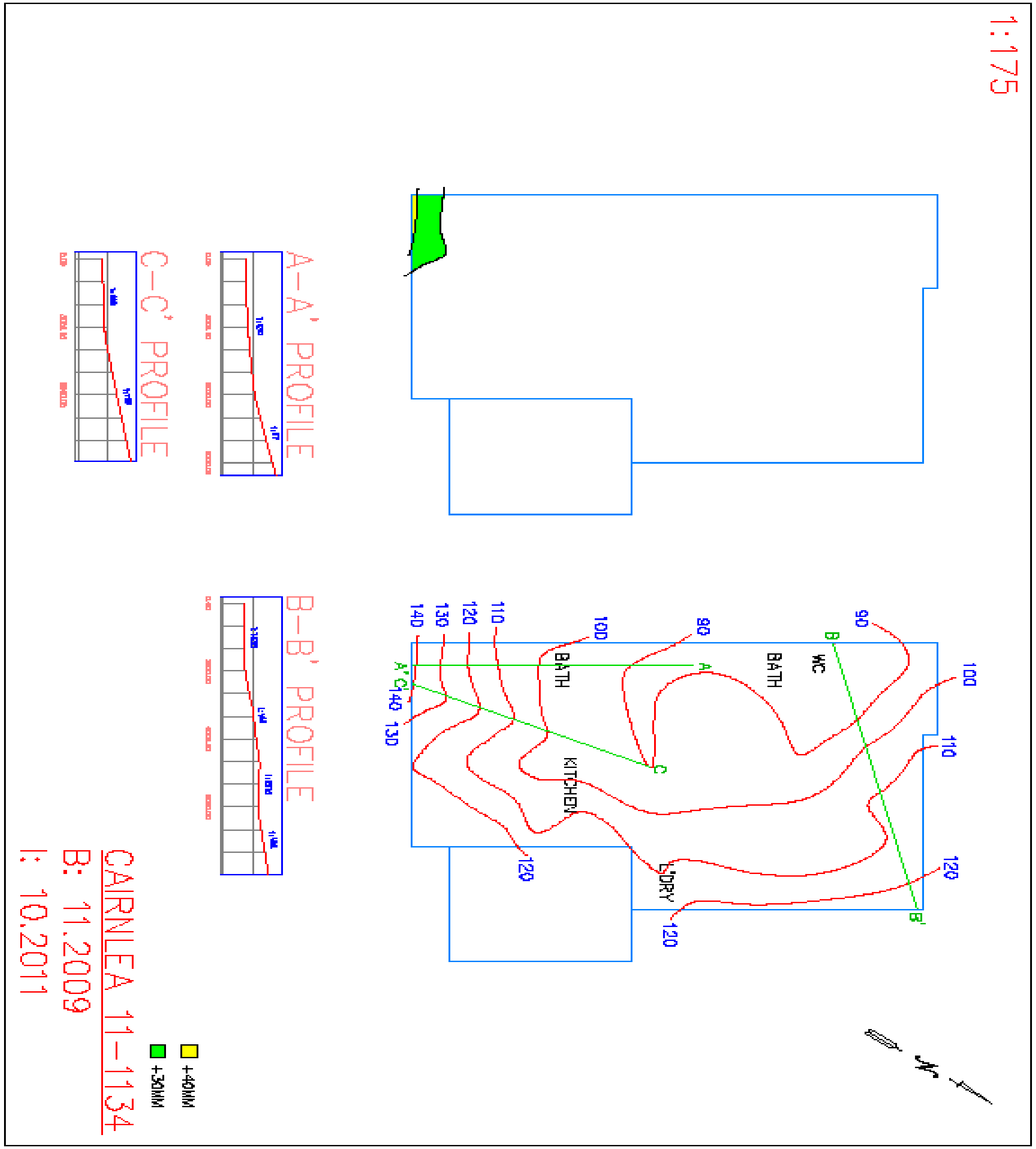
A
A'
B
B'
KITCHEN
PWD
L'DRY
110
100
90
120
A–A' PROFILE
B–B' PROFILE
CAIRNLEA 11–1137
B: 08.2008
I: 12.2011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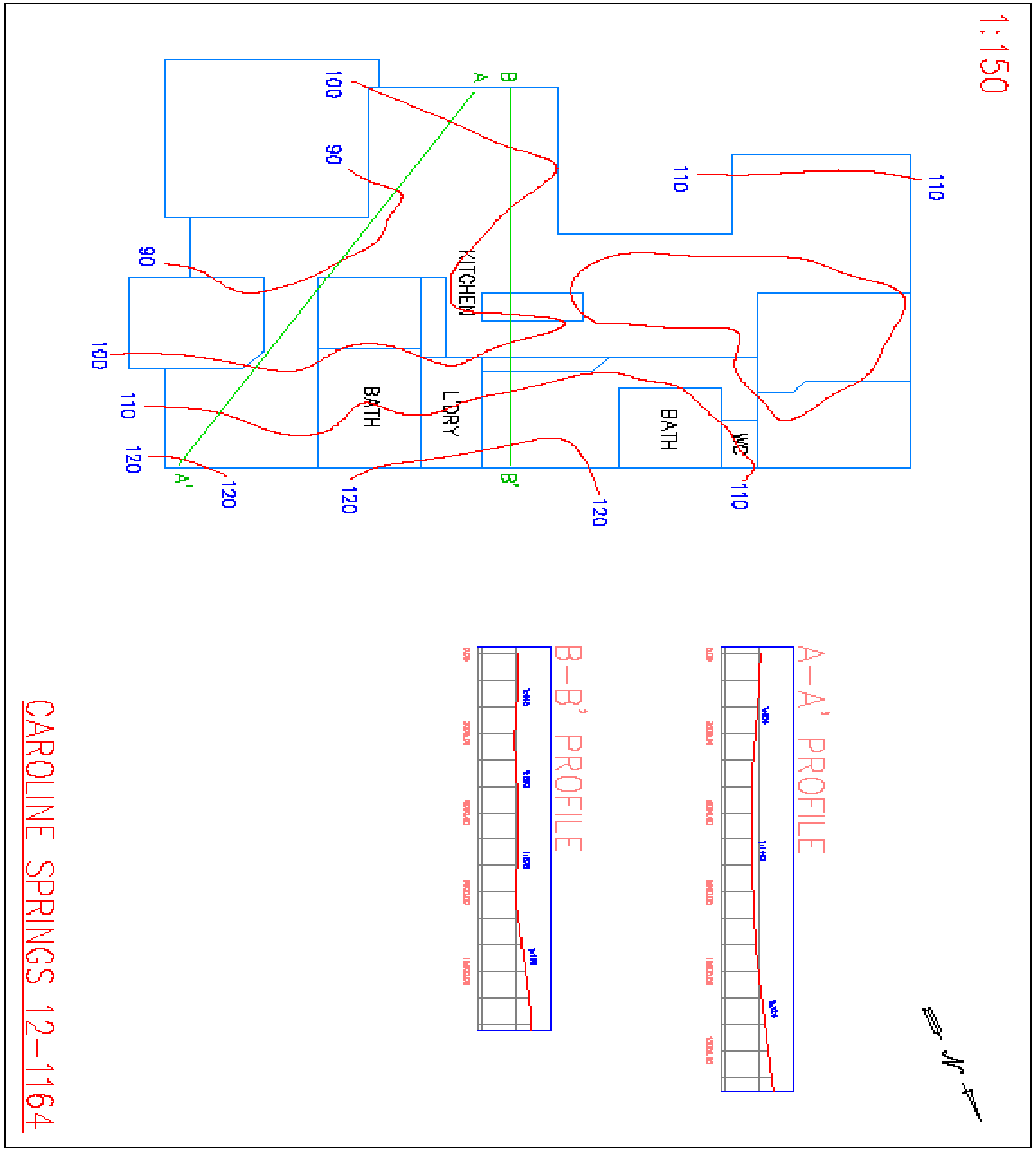
B–B' PROFILE
C–C' PROFILE
BATH
WC
BATH
KITCHEN
L'DRY
CAIRNLEA 11–1134
B: 11.2009
I: 10.2011
+40MM
+30MM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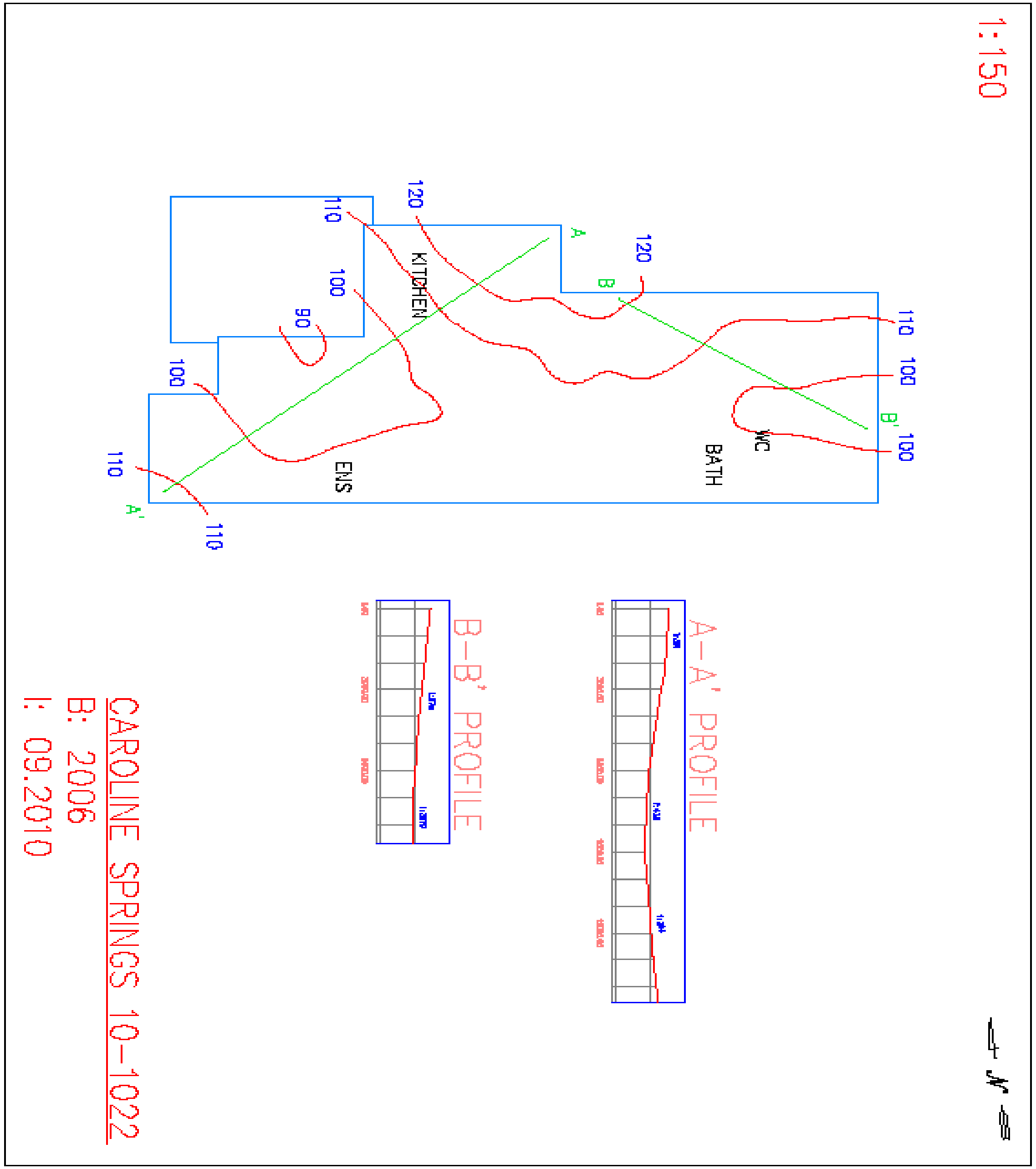
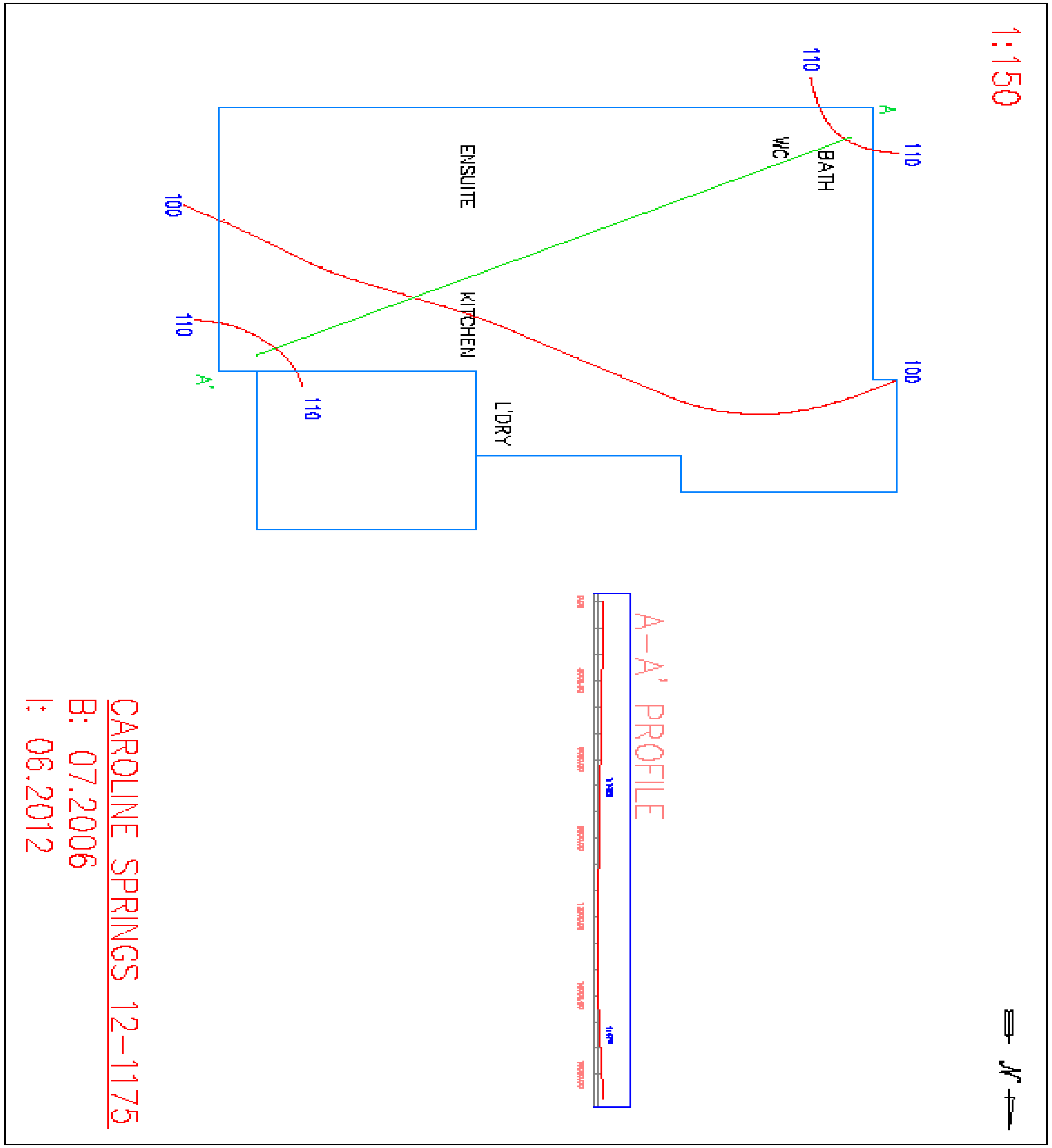
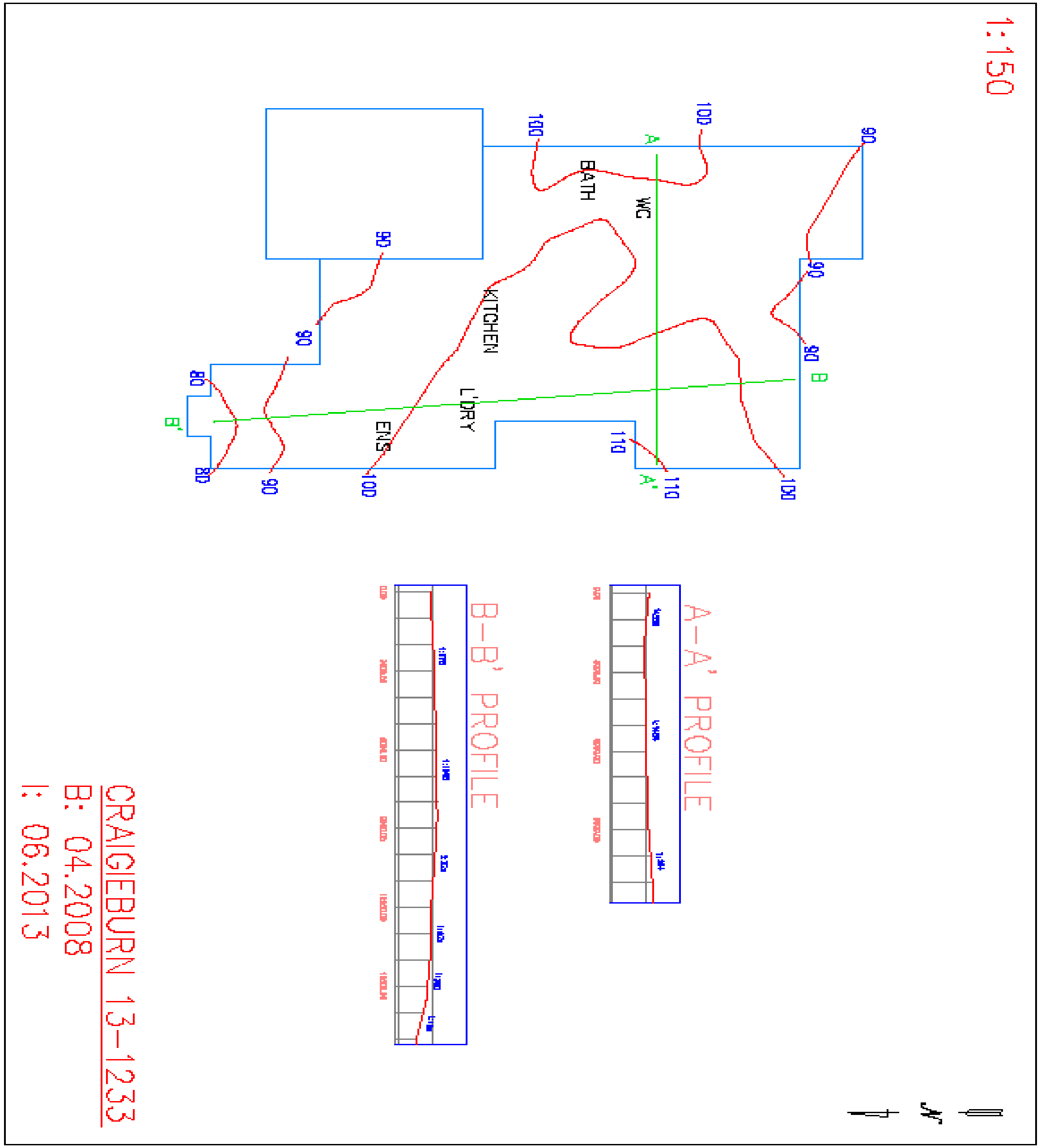
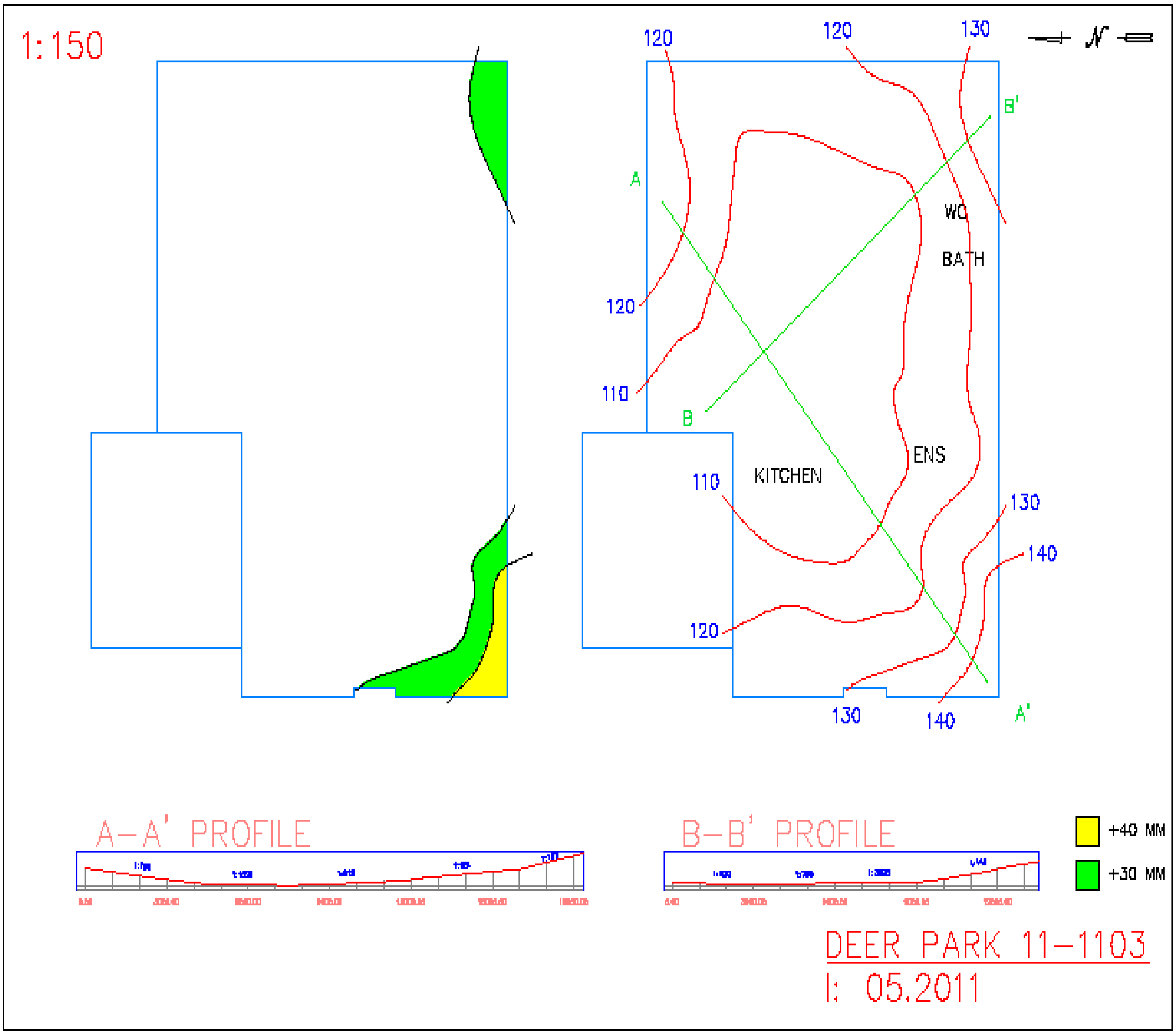
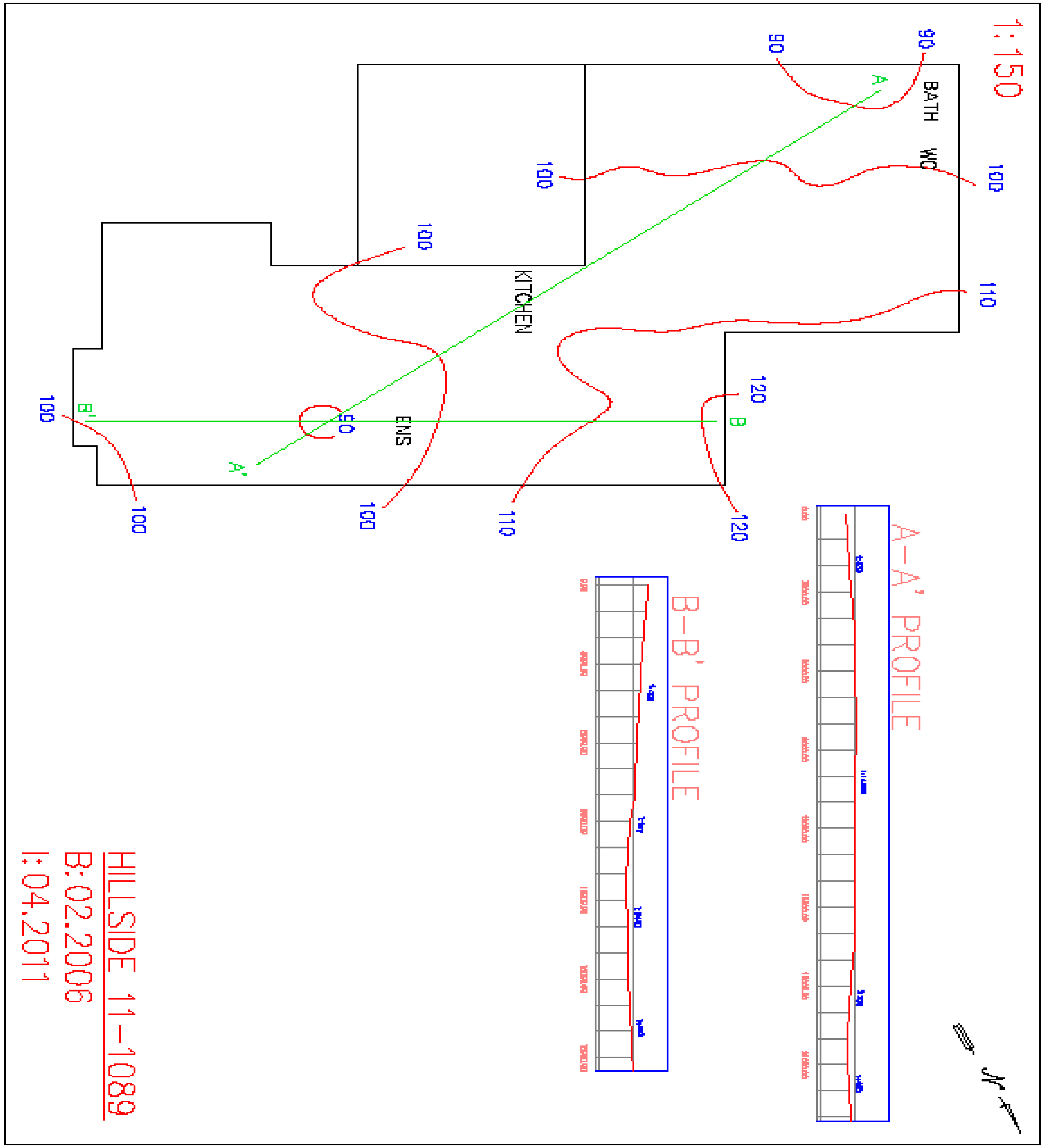
KITCHEN
BATH
LDRY
BATH
WC
A-A' PROFILE
B-B' PROFILE
CAROLINE SPRINGS 12-1164

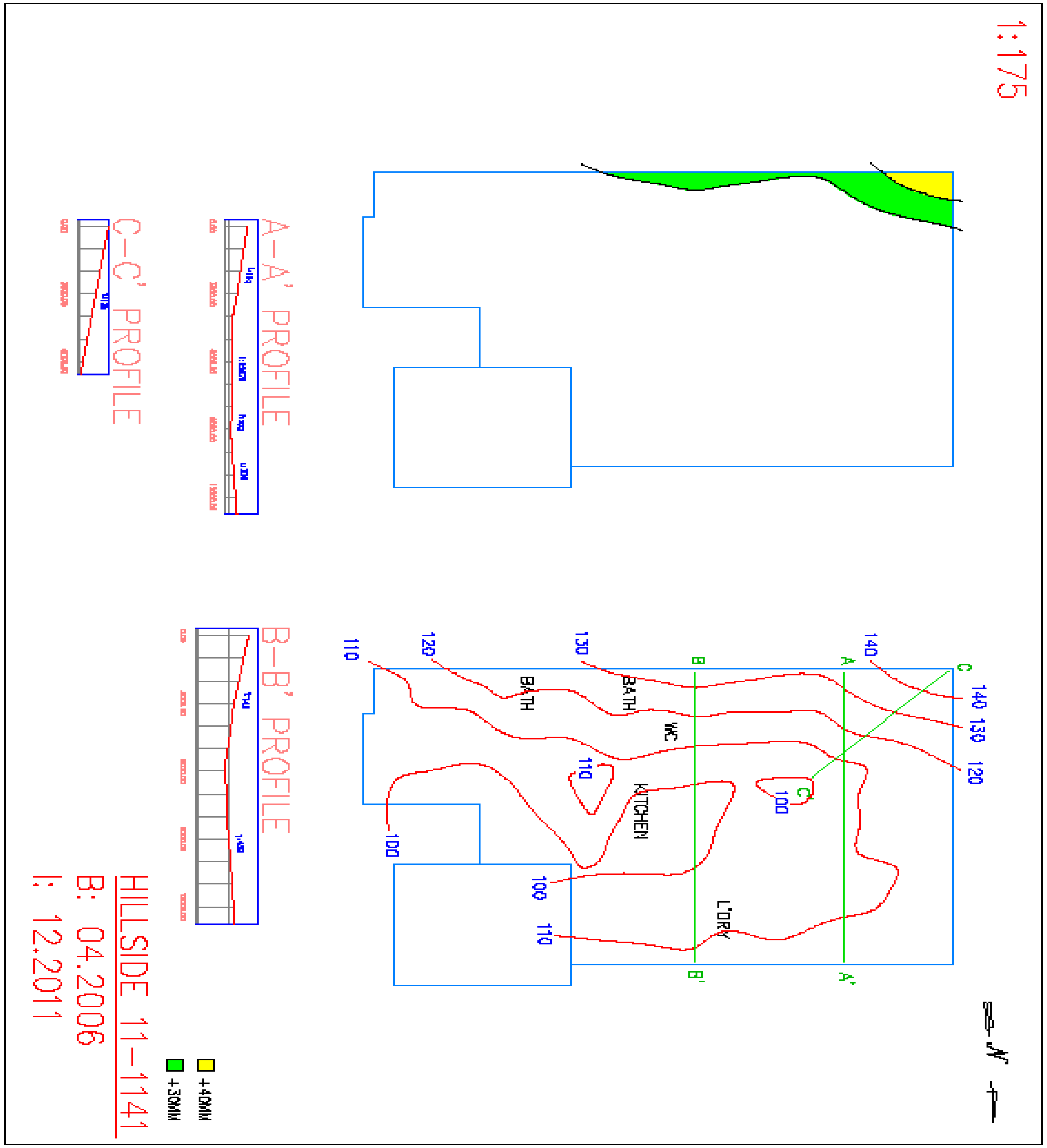

1:150
KITCHEN
ENS
BATH
WC
A-A' PROFILE
B-B' PROFILE
CAROLINE SPRINGS 10-1022
B: 2006
I: 09.2010

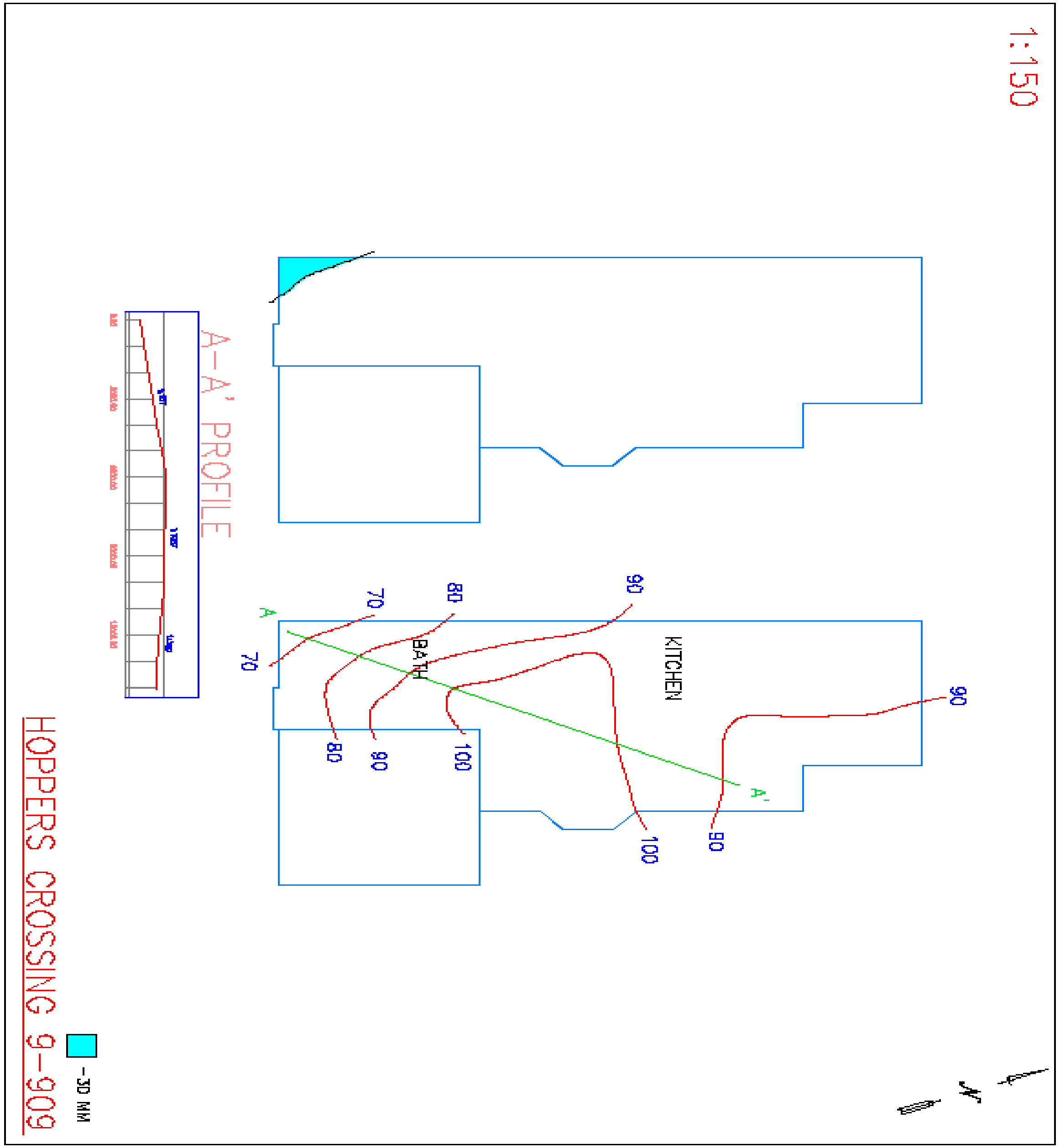

1:150
110
110
A
WC
BATH
ENSUITE
100
KITCHEN
110
100
A'
110
L'DRY
A-A' PROFILE
N
CAROLINE SPRINGS 12-1175
B: 07.2006
I: 06.2012

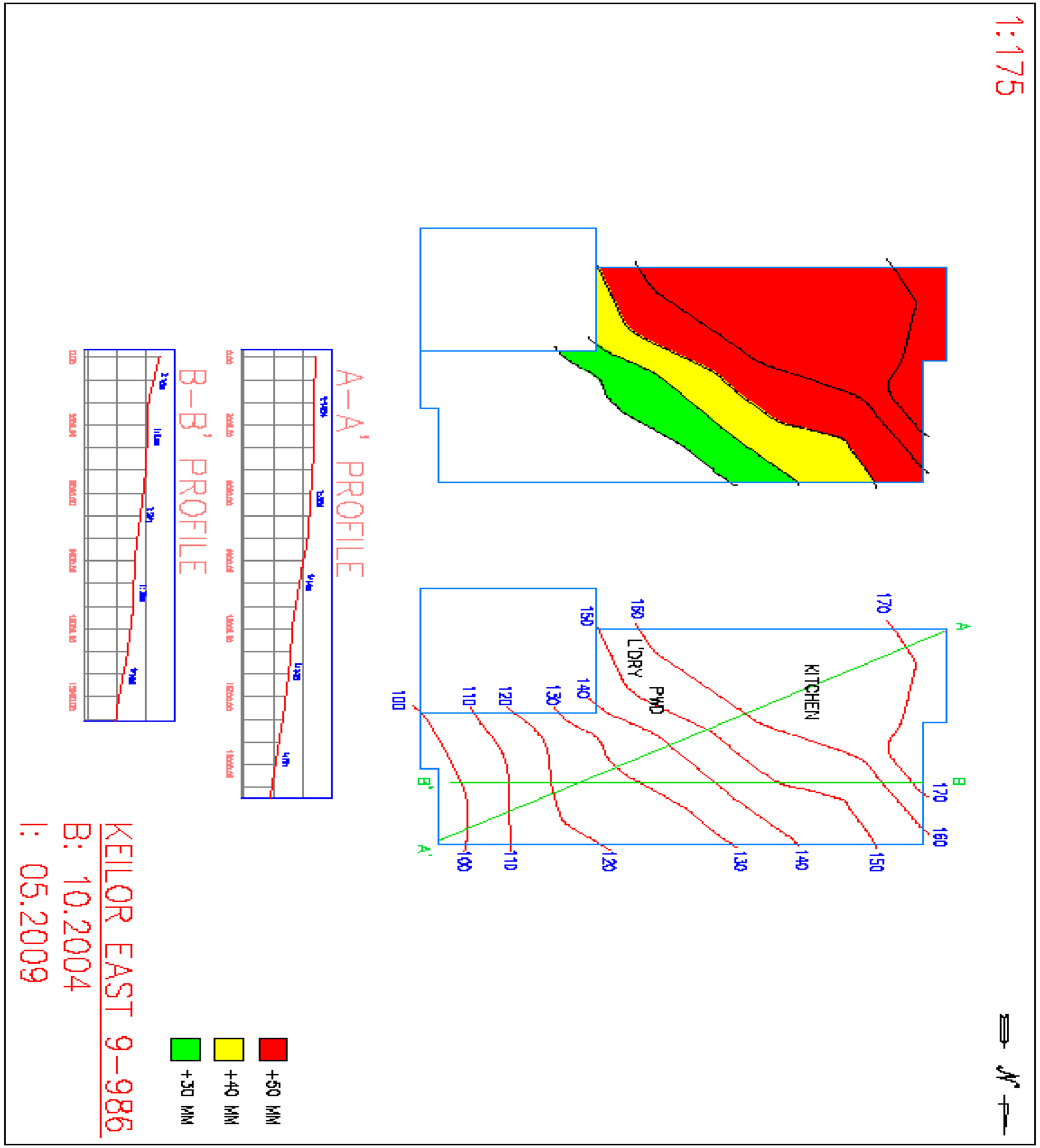

1:150
90
90
90
B
100
100
A
WC
110
A'
110
BATH
100
KITCHEN
L'DRY
90
ENS
100
90
90
80
80
B'
A–A' PROFILE
B–B' PROFILE
CRAIGIEBURN 13–1233
B: 04.2008
I: 06.2013


1:150
120
120
130
A
B'
WC
BATH
120
110
B
ENS
KITCHEN
110
130
140
120
130
140
A'
A–A' PROFILE
B–B' PROFILE
+40 MM
+30 MM
DEER PARK 11–1103
I: 05.2011


1:150
BATH
WC
KITCHEN
ENS
A-A' PROFILE
B-B' PROFILE
HILLSIDE 11-1089
B:02.2006
I:04.2011


1:175
A-A' PROFILE
C-C' PROFILE
B-B' PROFILE
BATH
BATH
WC
KITCHEN
L'DRY
+40MM
+30MM
HILLSIDE 11-1141
B: 04.2006
I: 12.2011


1:150
A-A' PROFILE
HOPPERS CROSSING 9-909
-30 MM
KITCHEN
BATH
A
A'
70
80
90
100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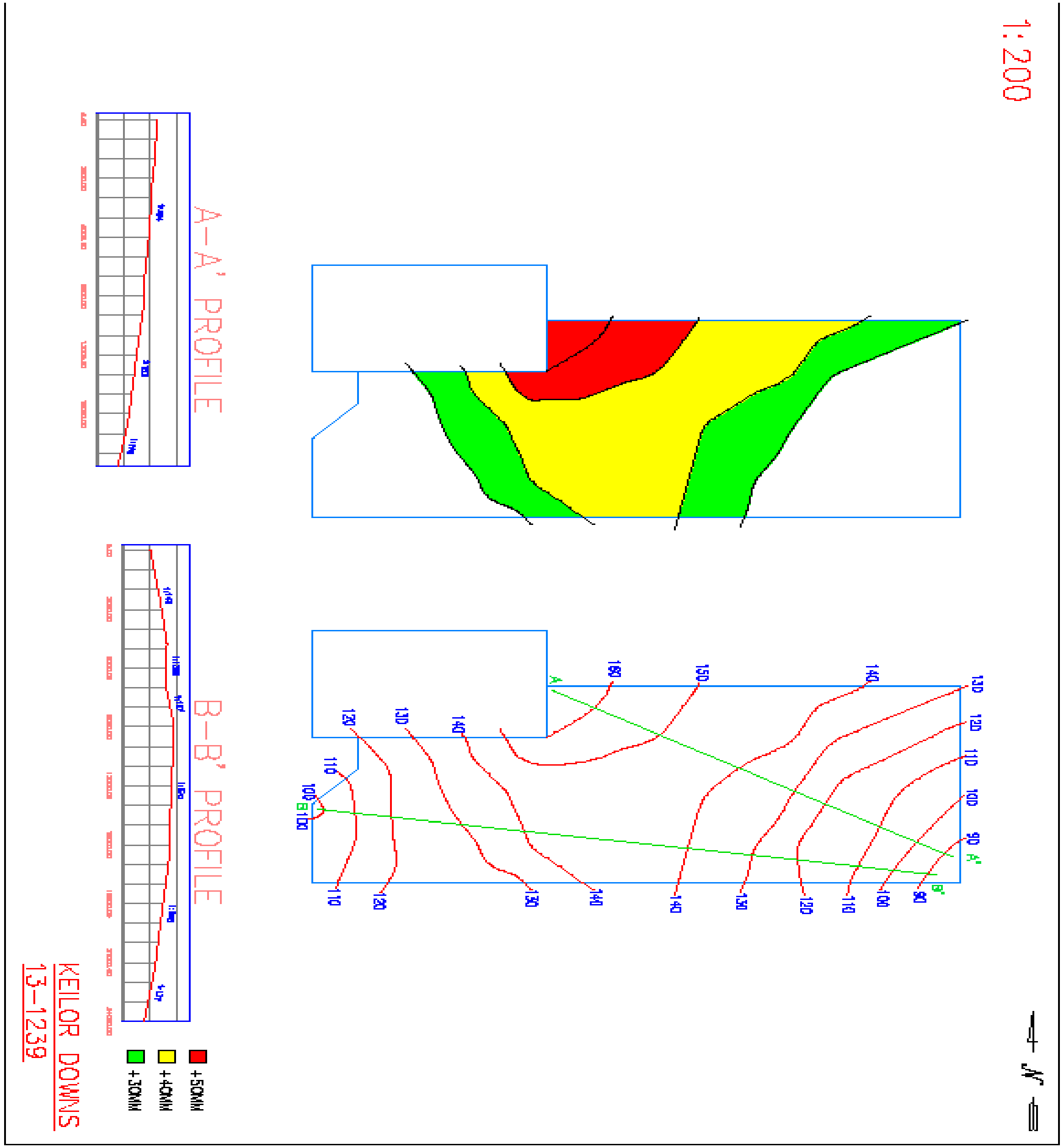
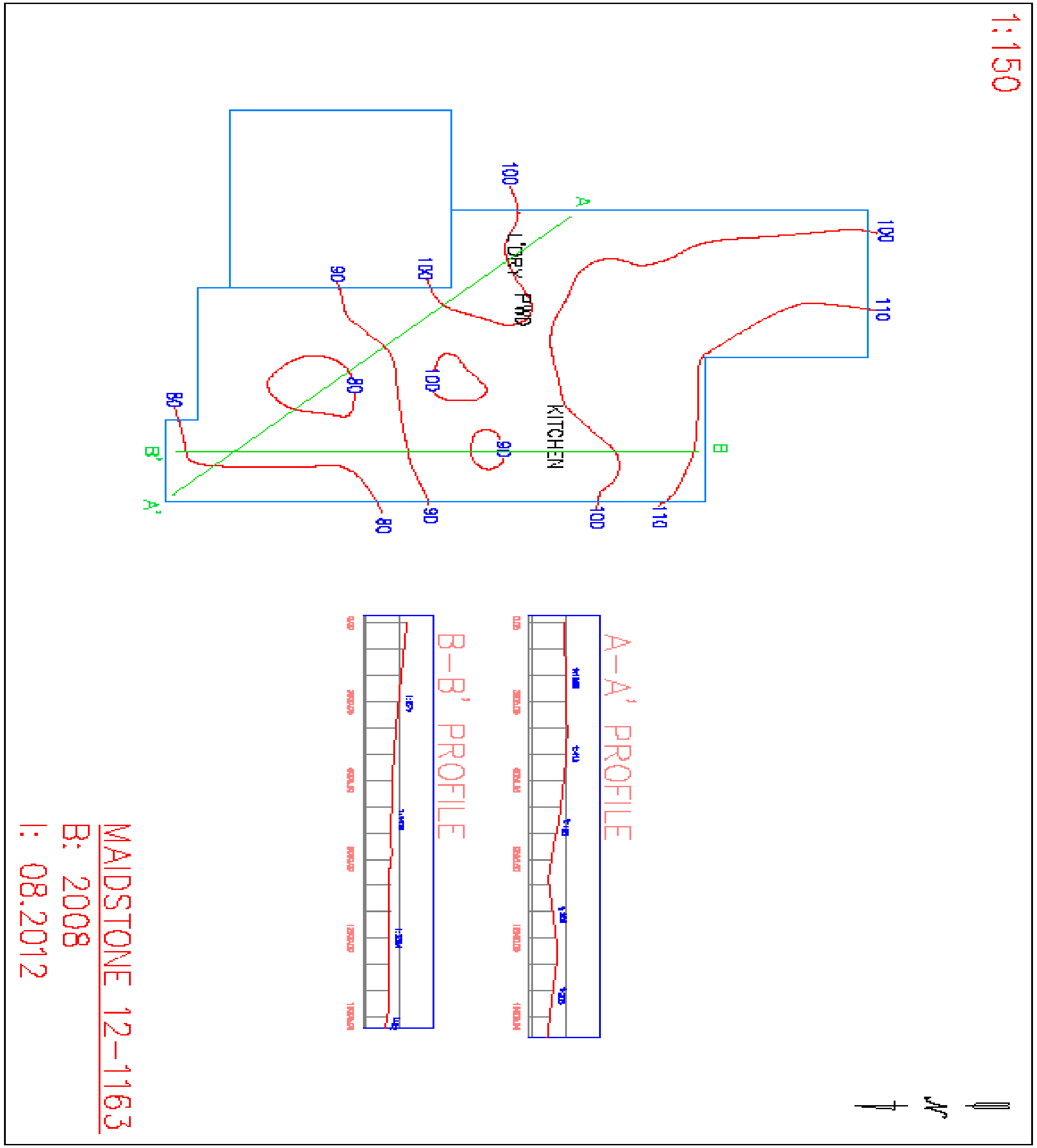
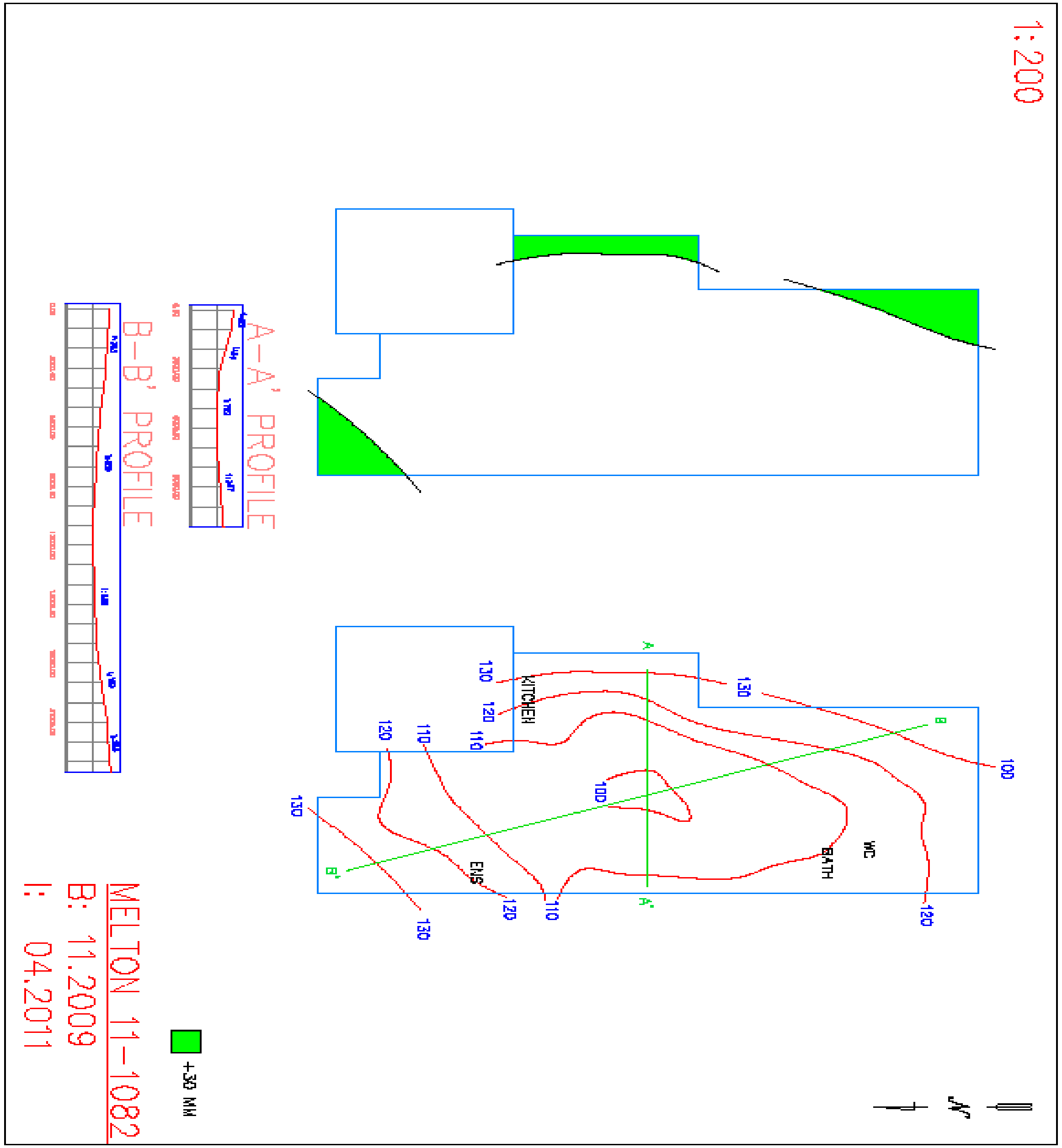
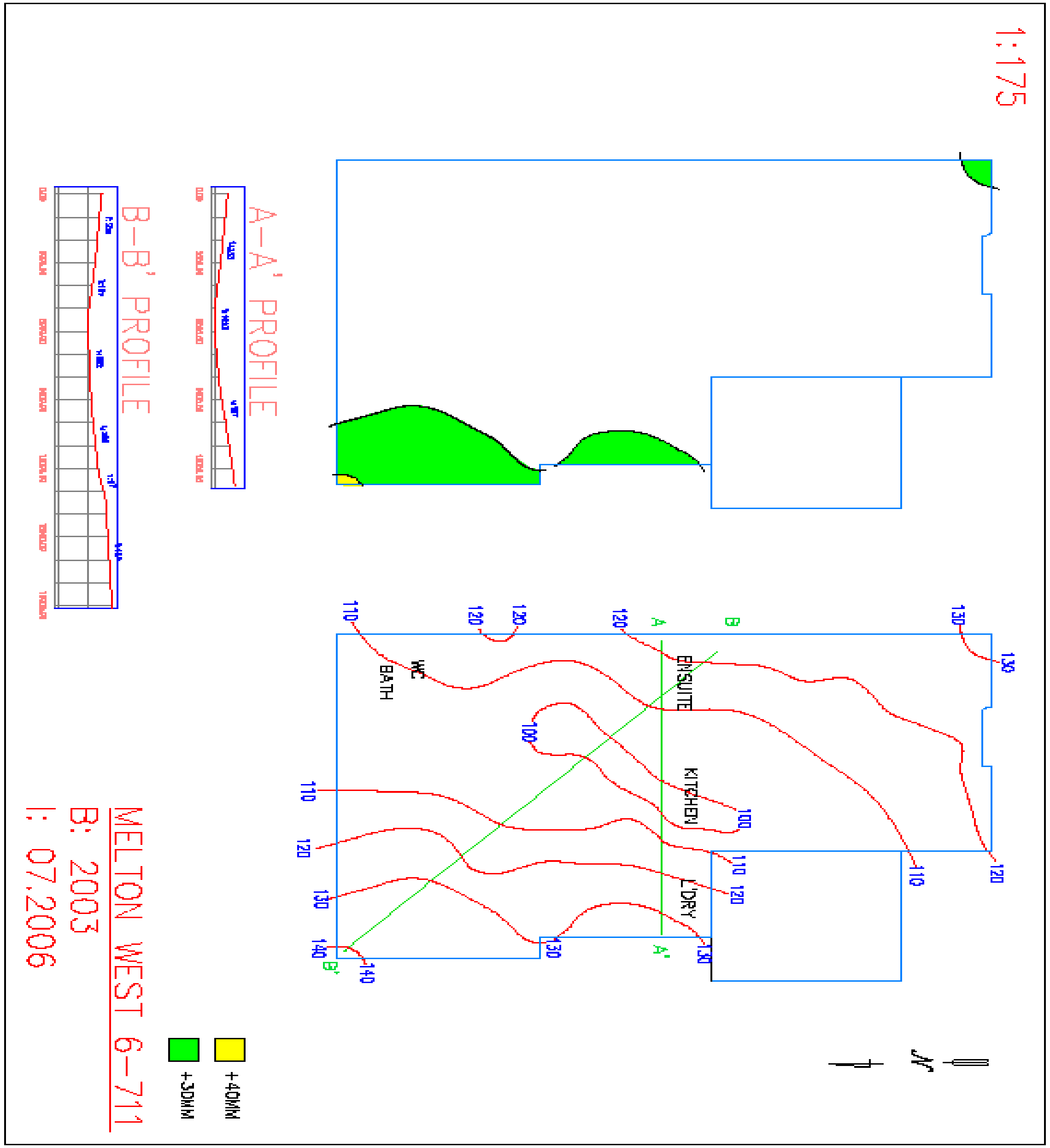
KITCHEN
L'DRY
PWD
A
A'
B
B'
100
110
120
130
140
150
160
170
A–A' PROFILE
B–B' PROFILE
+50 MM
+40 MM
+30 MM
KEILOR EAST 9–986
B: 10.2004
I: 05.2009

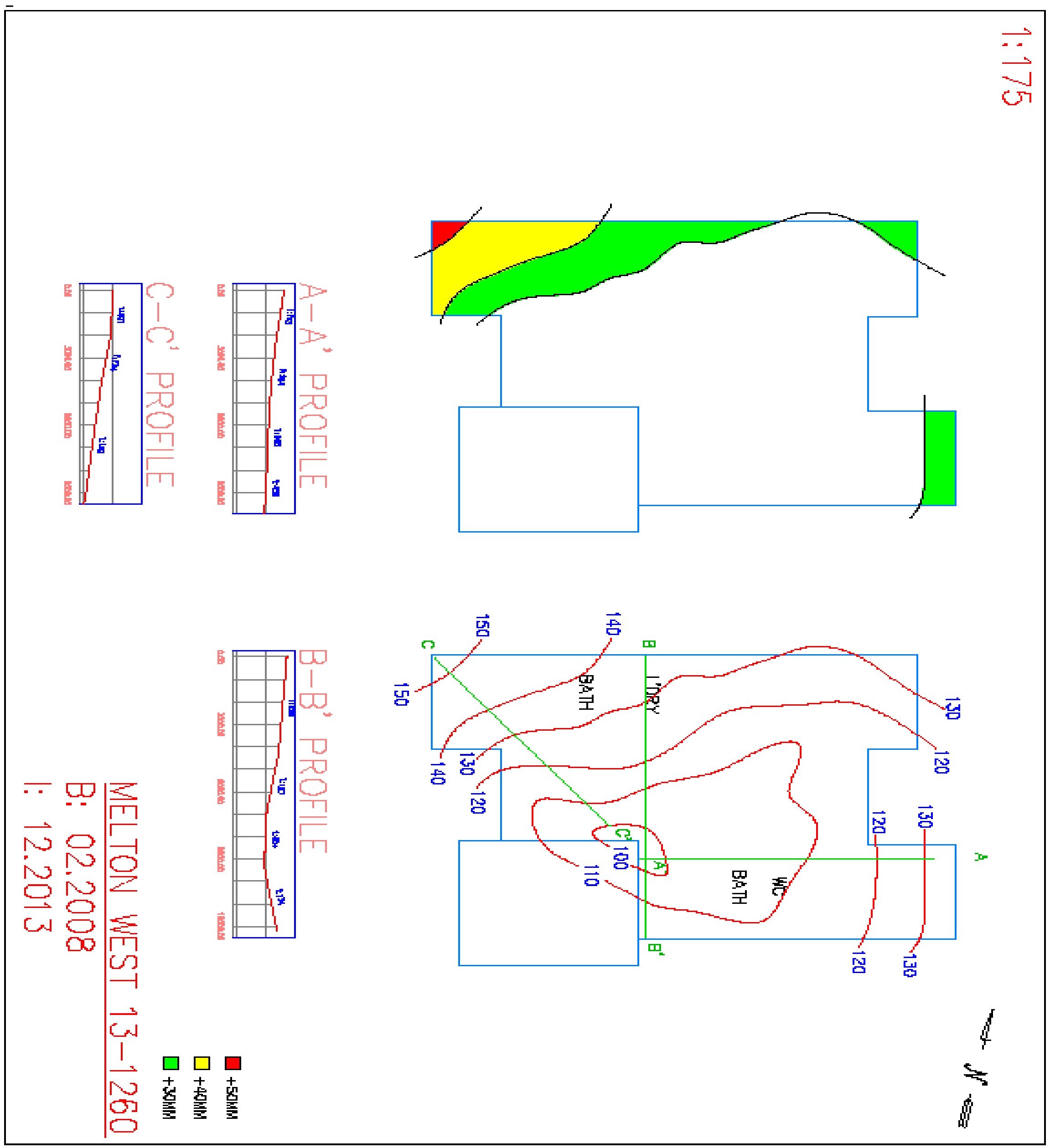

1:200
A-A' PROFILE
B-B' PROFILE
+50MM
+40MM
+30MM
KEILOR DOWNS
13-1239

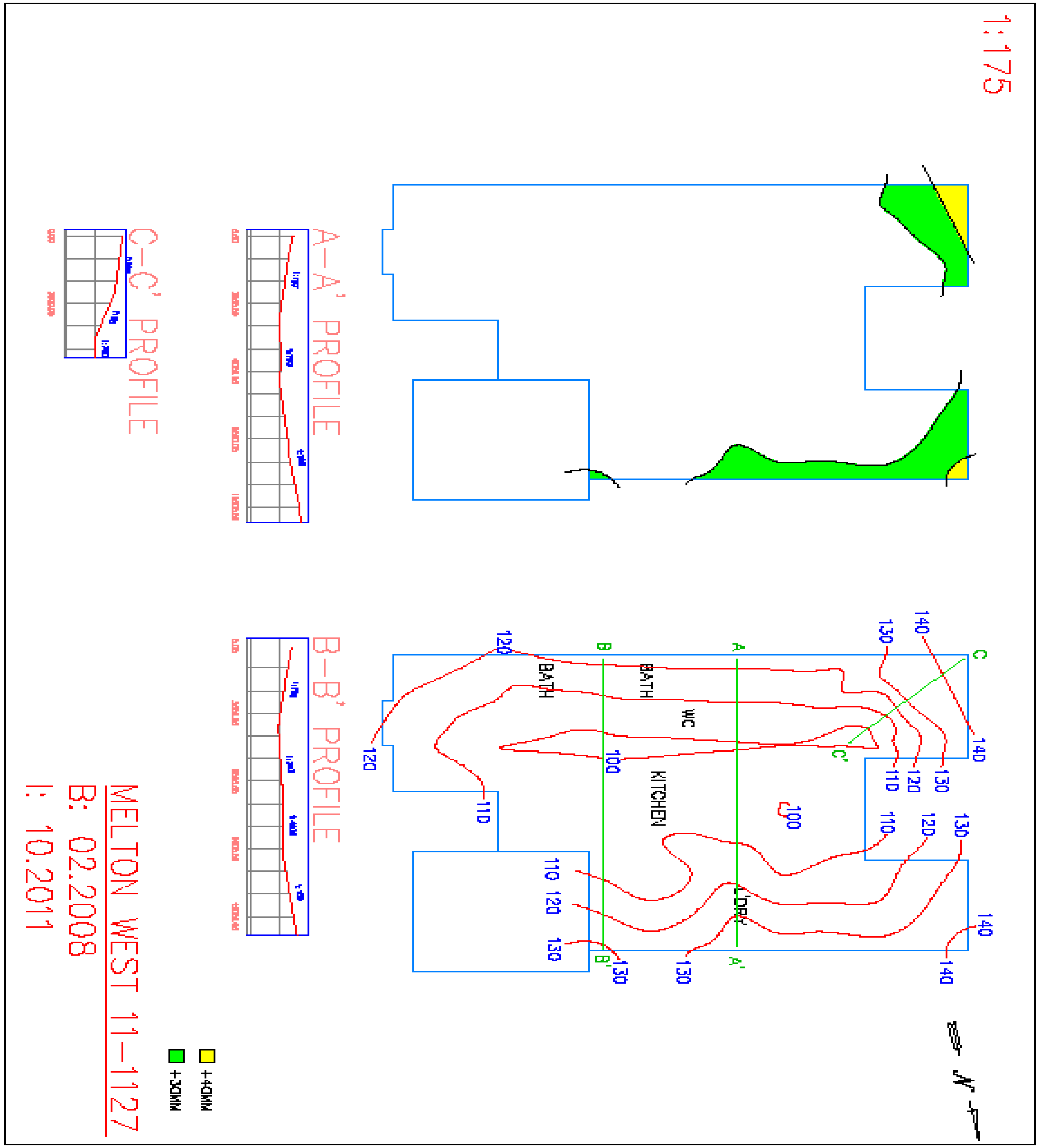

1:150
L'DRY
PWD
KITCHEN
A
A'
B
B'
A–A' PROFILE
B–B' PROFILE
MAIDSTONE 12–1163
B: 2008
I: 08.2012


1:200
A–A' PROFILE
B–B' PROFILE
KITCHEN
ENS
BATH
WC
+30 MM
MELTON 11–1082
B: 11.2009
I: 04.2011



1:175
A–A' PROFILE
B–B' PROFILE
WC
BATH
ENSUITE
KITCHEN
L'DRY
+40MM
+30MM
MELTON WEST 6–711
B: 2003
I: 07.2006


1:175
A–A' PROFILE
B–B' PROFILE
C–C' PROFILE
BATH
L'DRY
BATH
WC
150
140
130
120
110
100
+50MM
+40MM
+30MM
MELTON WEST 13–1260
B: 02.2008
I: 12.2013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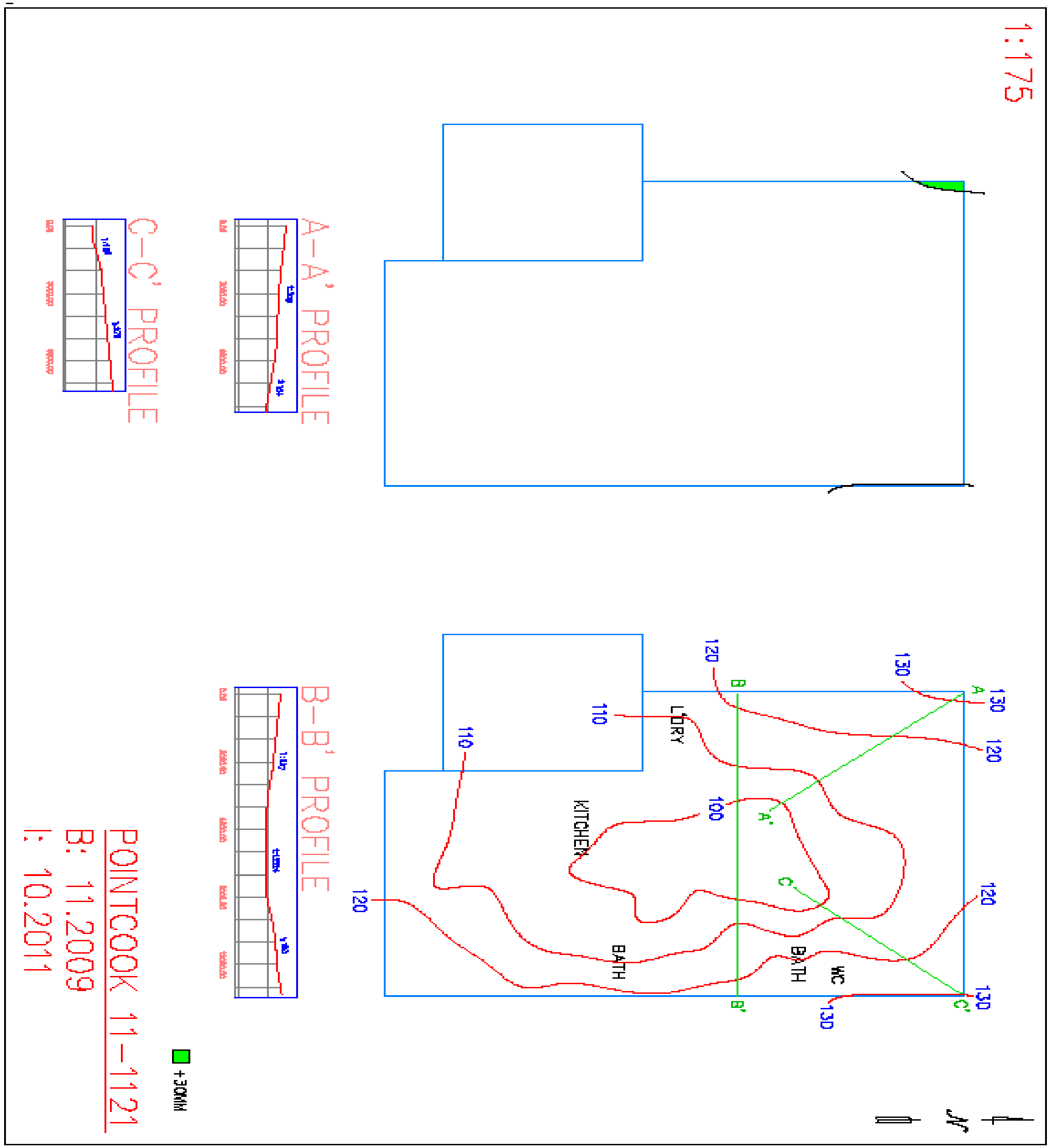
B–B' PROFILE
C–C' PROFILE
BATH
WC
KITCHEN
LDRY
+40MM
+30MM
MELTON WEST 11–1127
B: 02.2008
I: 10.2011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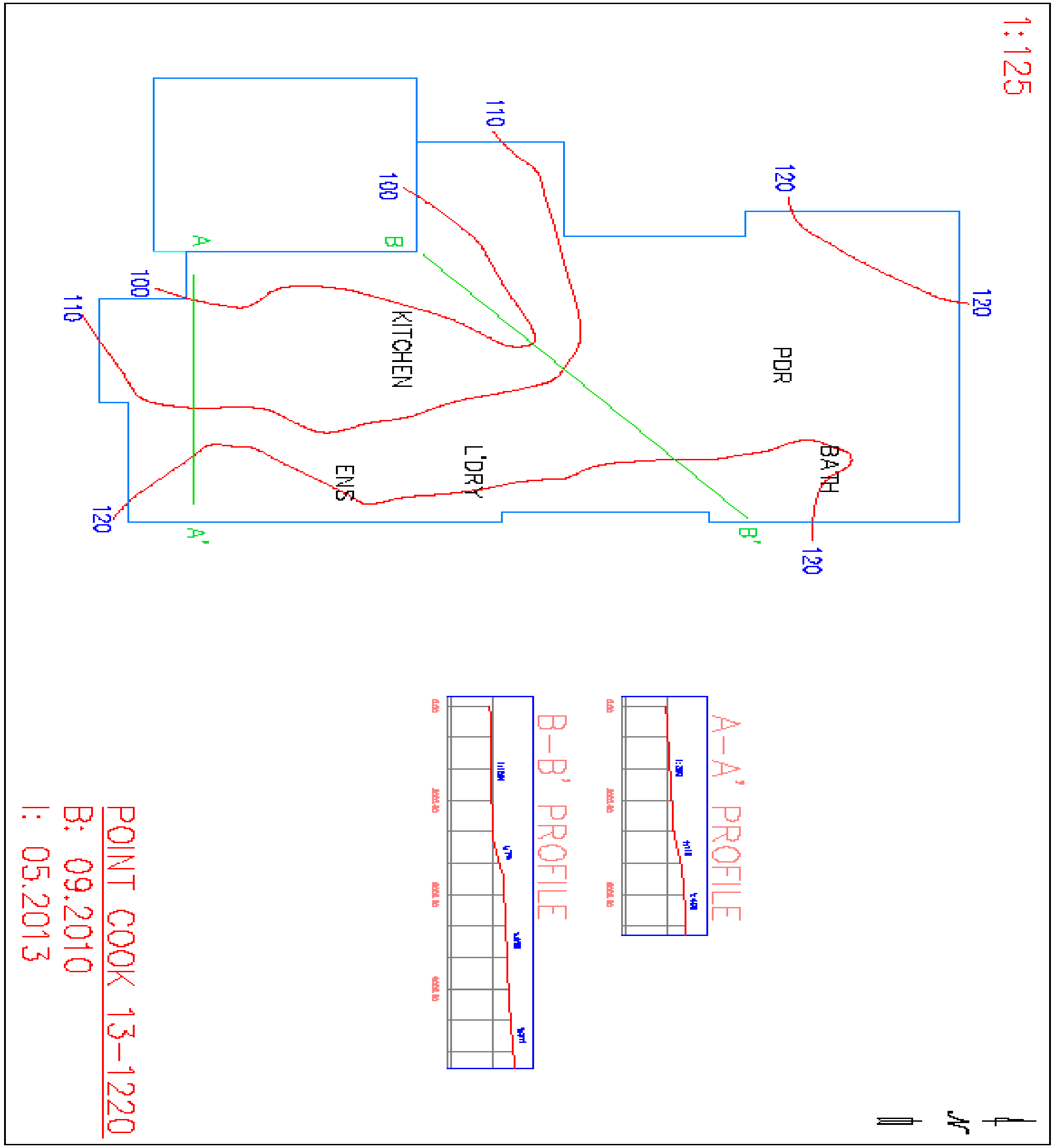
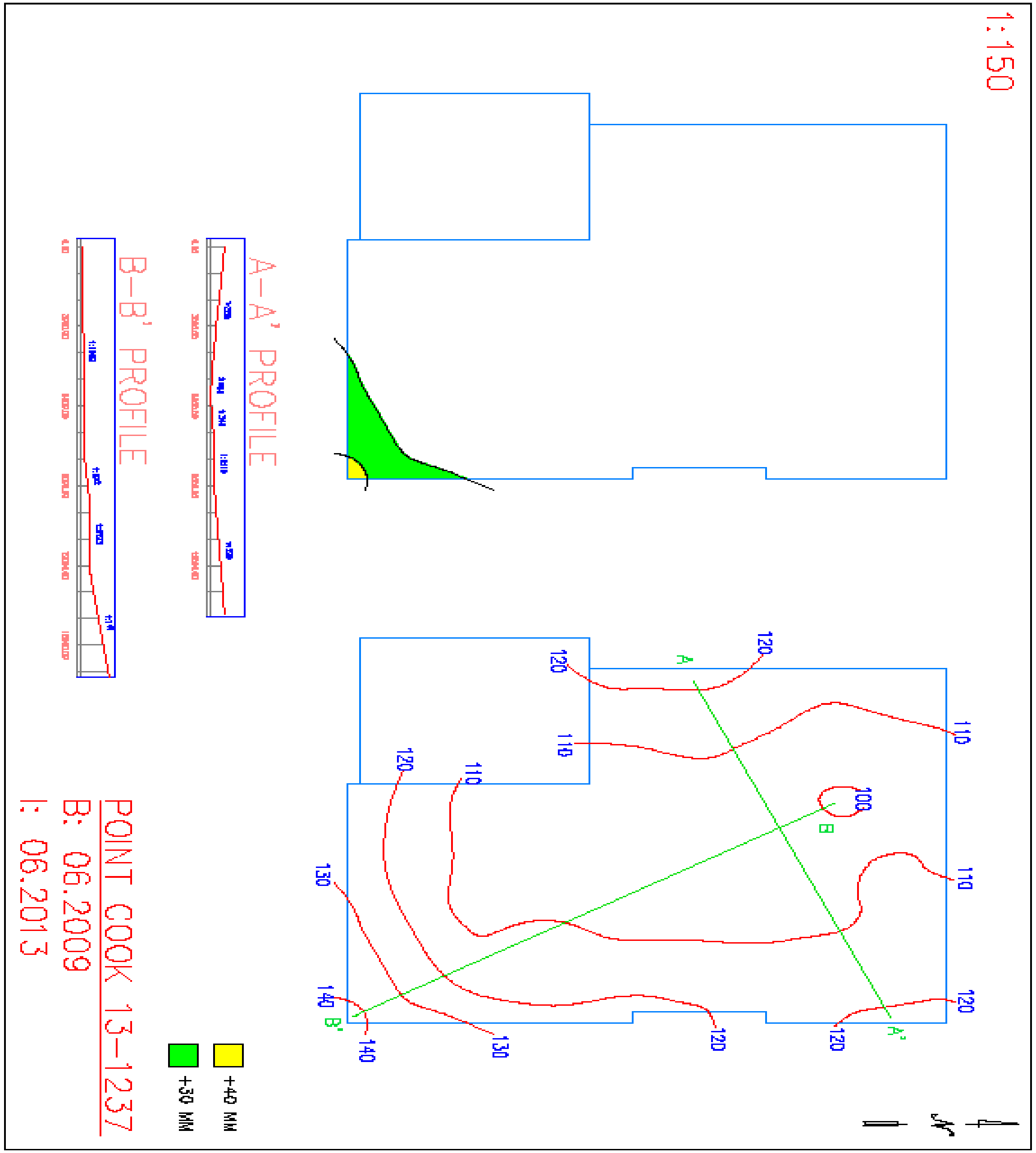
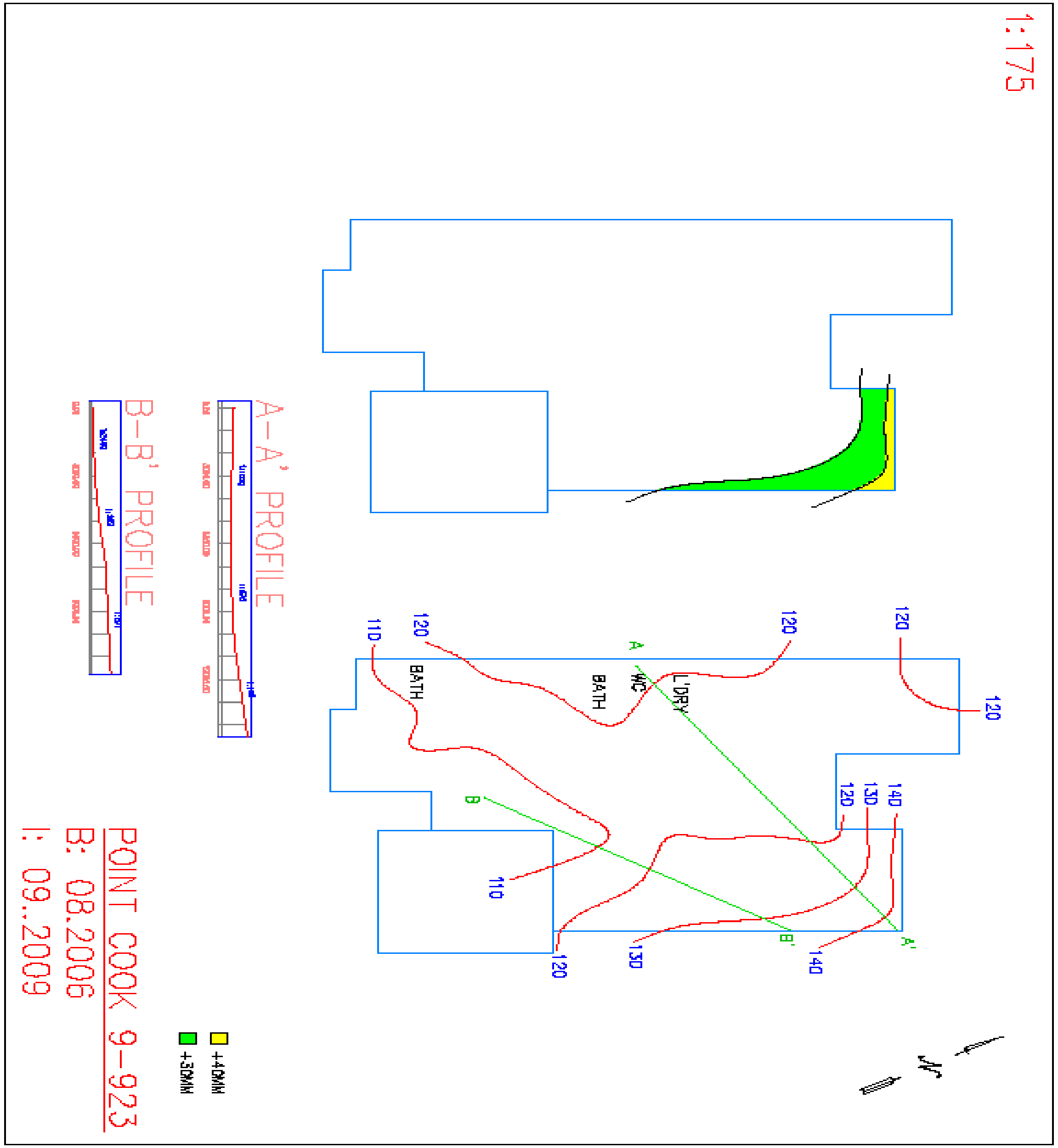
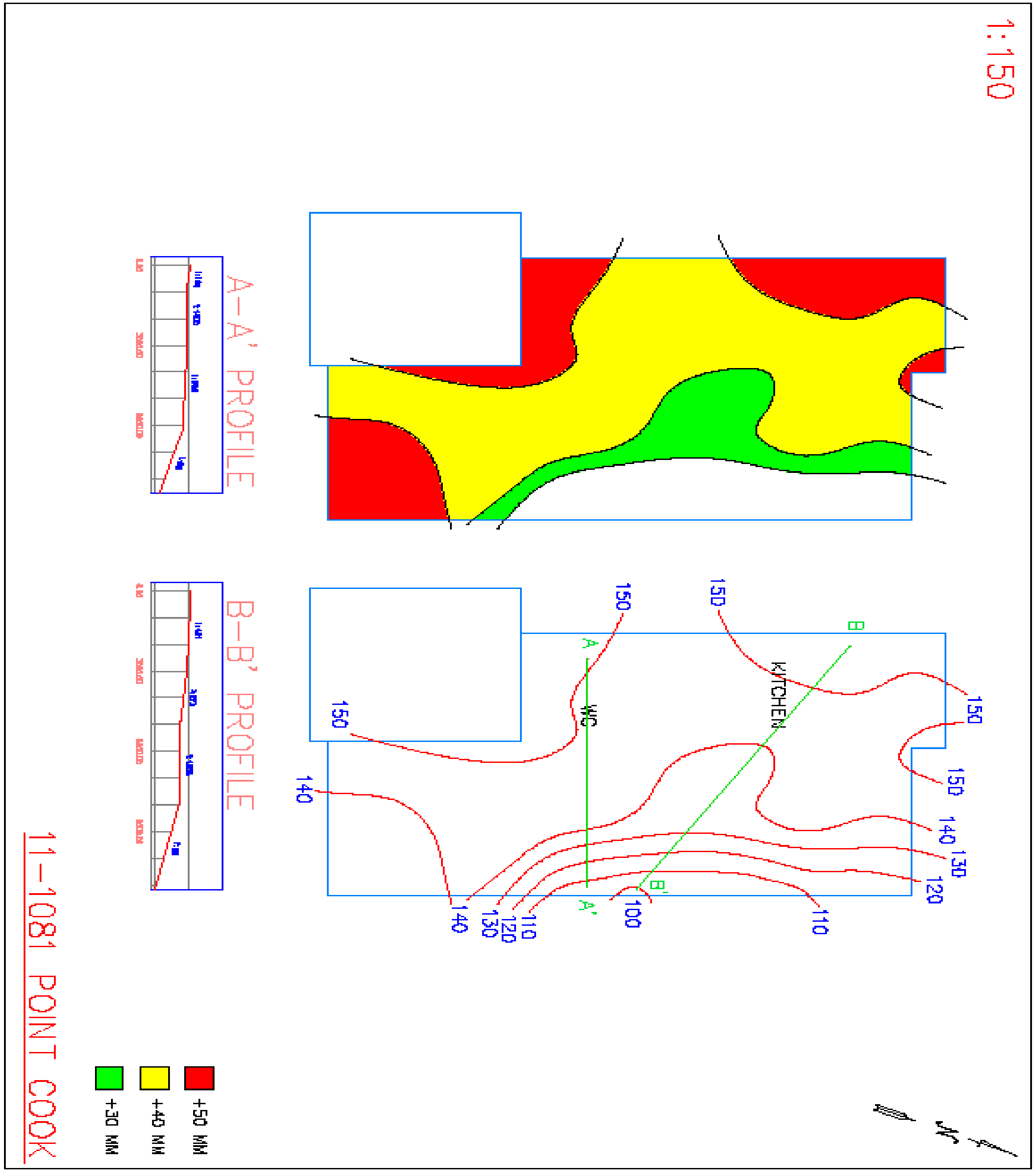
A–A' PROFILE
C–C' PROFILE
B–B' PROFILE
LDRY
KITCHEN
BATH
BATH
WC
+30MM
POINTCOOK 11–1121
B: 11.2009
I: 10.2011


1:125
110
120
100
A
B
KITCHEN
PDR
L'DRY
ENS
BATH
A'
B'
A–A' PROFILE
B–B' PROFILE
POINT COOK 13–1220
B: 09.2010
I: 05.2013

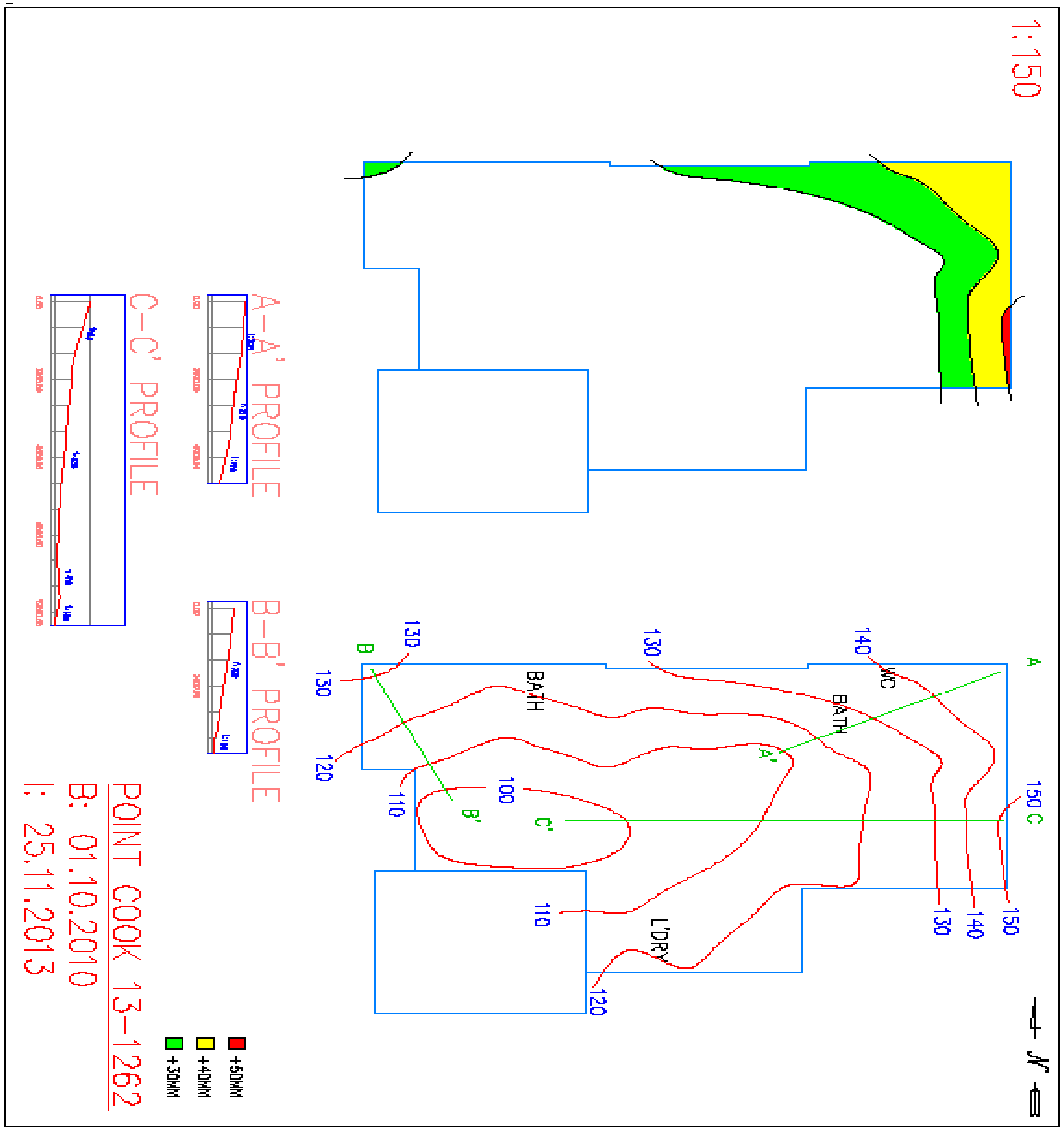


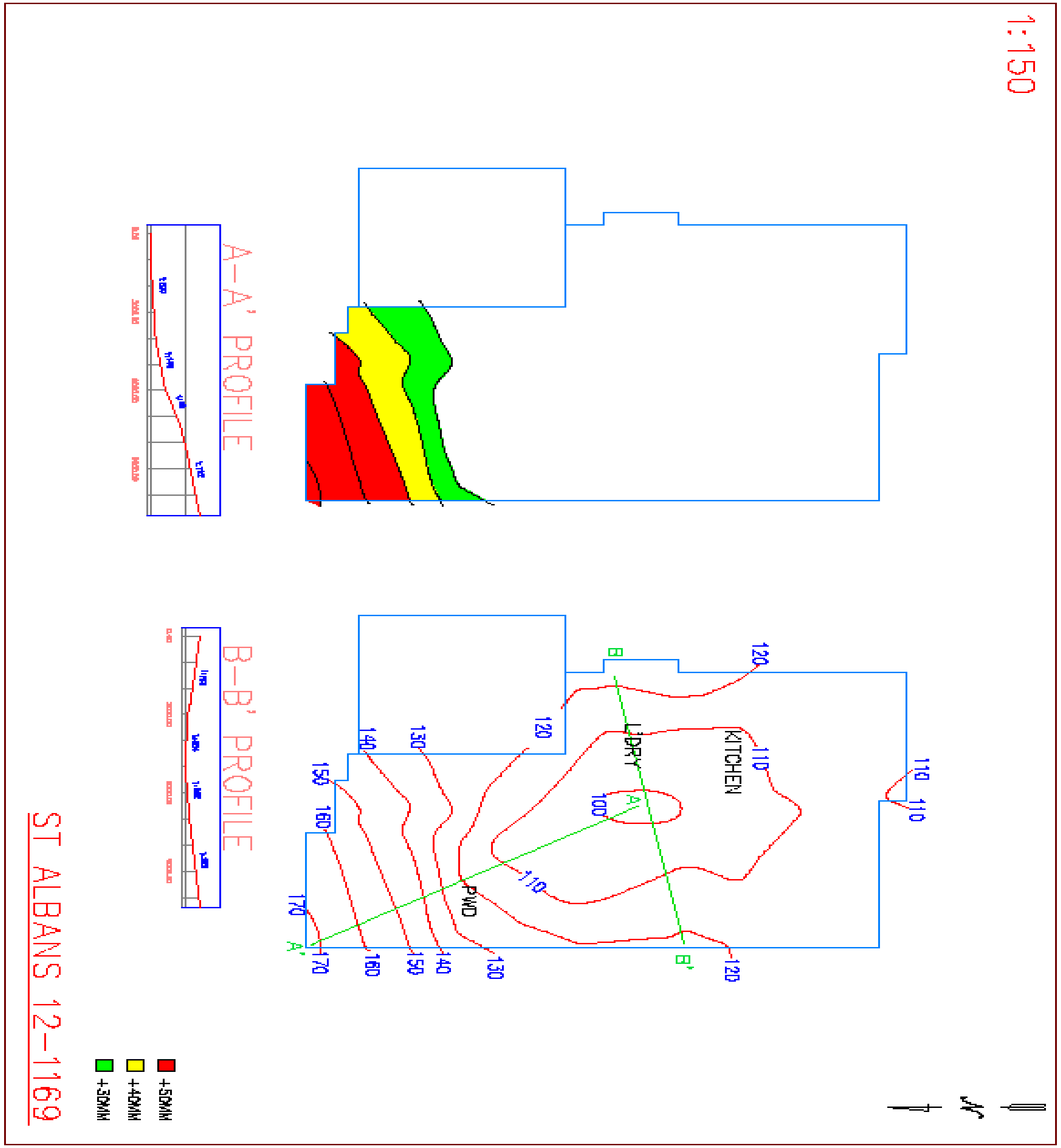
1:150
A-A' PROFILE
B-B' PROFILE
POINT COOK 13-1237
B: 06.2009
I: 06.2013
+40 MM
+30 MM

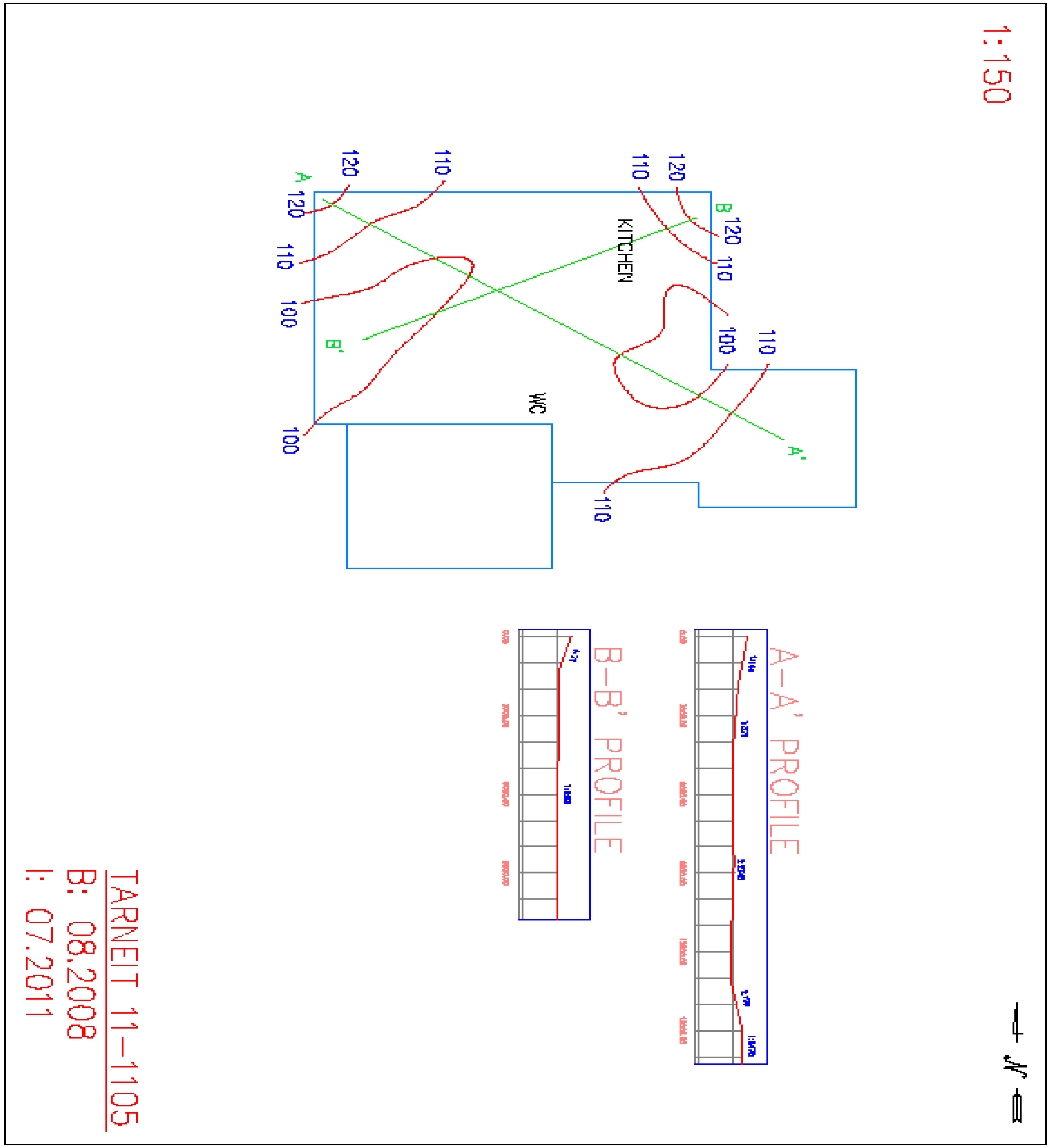

1:175
A-A' PROFILE
B-B' PROFILE
POINT COOK 9-923
B: 08.2006
I: 09.2009
+40MM
+30MM
BATH
BATH
WC
L'DRY
A
A'
B
B'
110
120
130
140

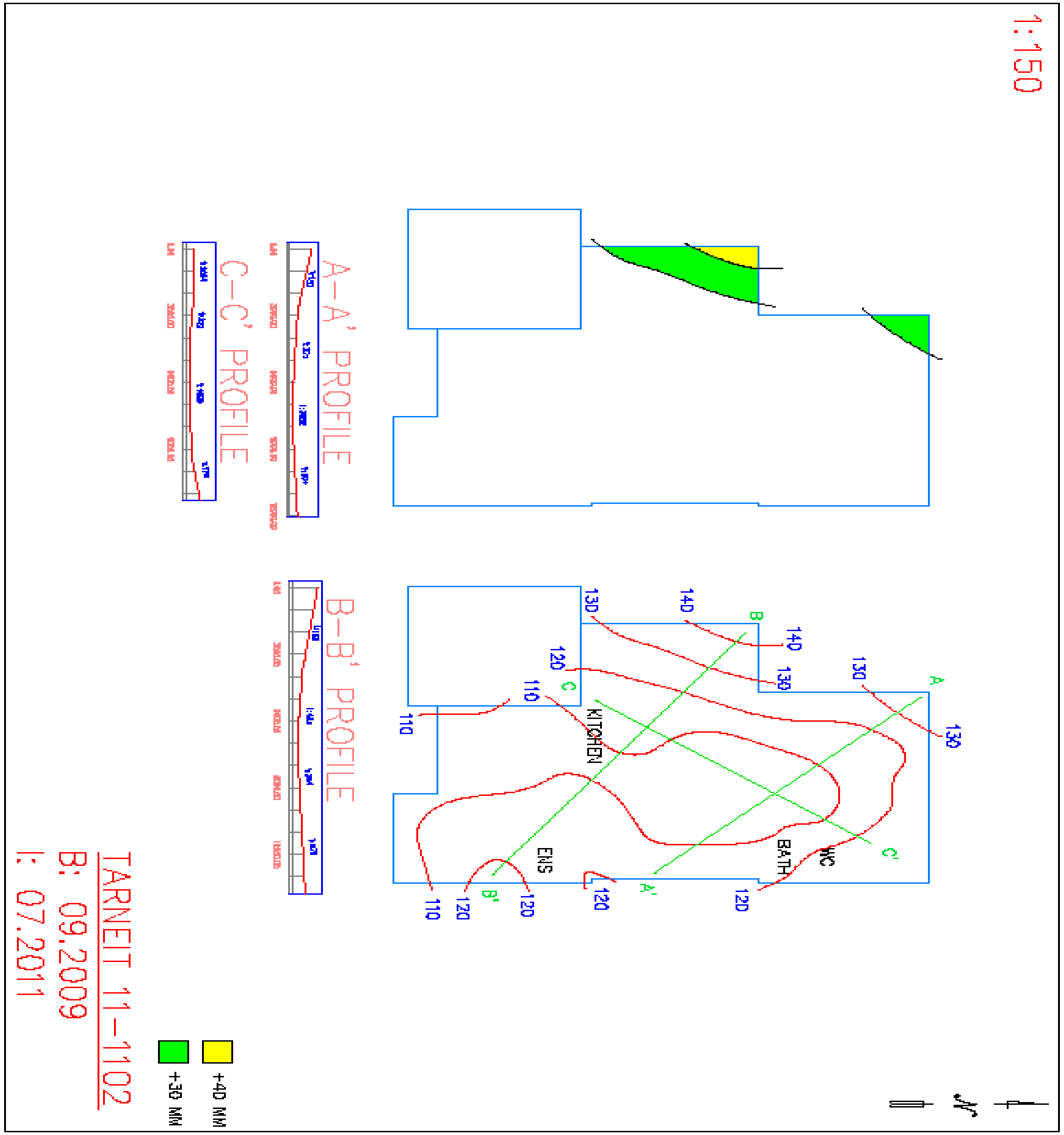


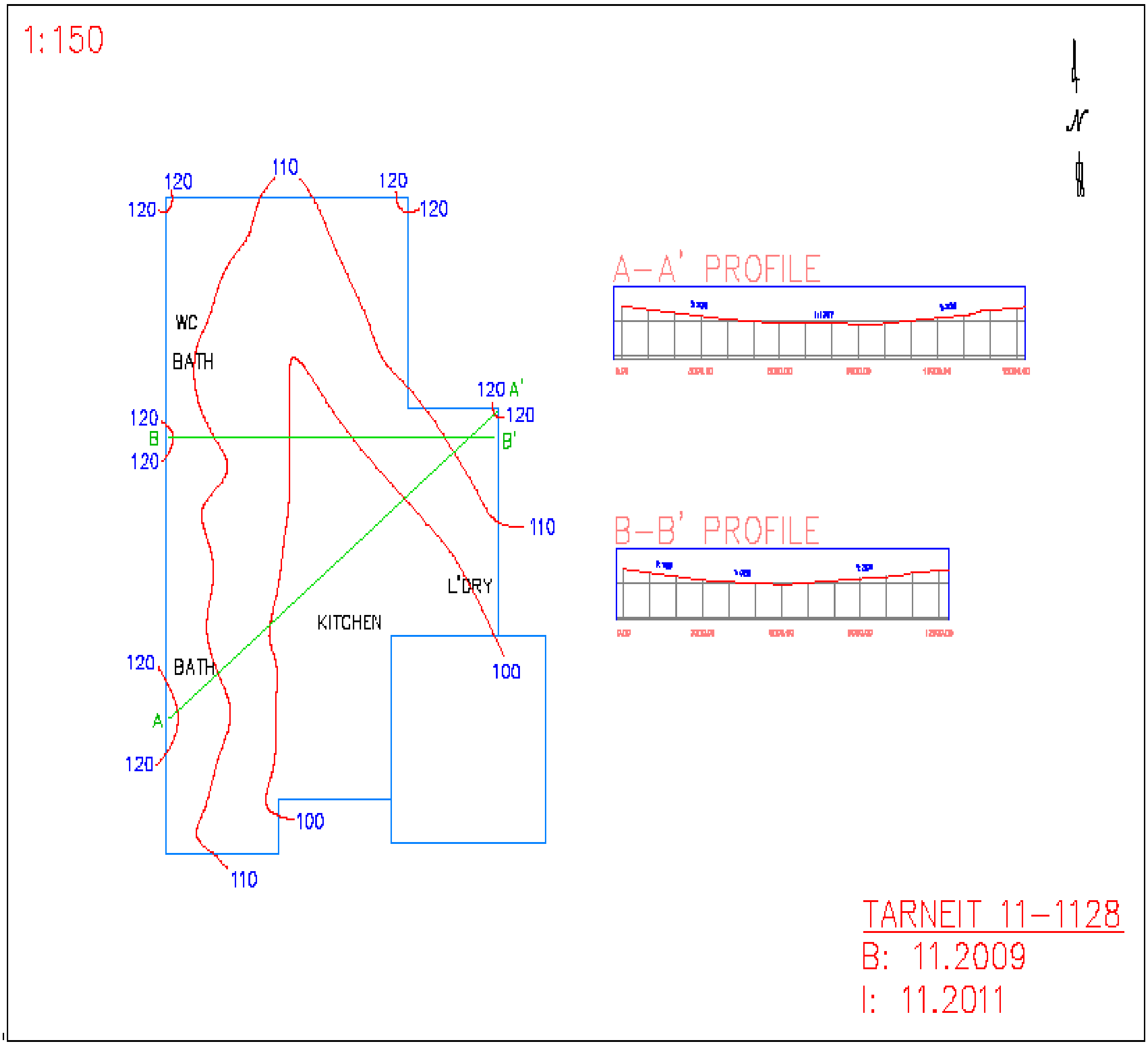
1:150
A–A' PROFILE
B–B' PROFILE
KITCHEN
WC
A
A'
B
B'
150
140
130
120
110
100
+50 MM
+40 MM
+30 MM
11–1081 POINT COOK


1:150
A
150 C
150
140
130
140
WC
BATH
A'
130
L'DRY
120
C'
110
BATH
100
B'
130
B
110
130
120
A–A' PROFILE
B–B' PROFILE
C–C' PROFILE
+50MM
+40MM
+30MM
POINT COOK 13–1262
B: 01.10.2010
I: 25.11.2013


1:150
A-A' PROFILE
B-B' PROFILE
KITCHEN
LDRY
PWD
ST ALBANS 12-1169
+50MM
+40MM
+30MM


1:150
KITCHEN
WC
A
A'
B
B'
120
110
100
A-A' PROFILE
B-B' PROFILE
TARNEIT 11-1105
B: 08.2008
I: 07.2011


1:150
A-A' PROFILE
C-C' PROFILE
B-B' PROFILE
KITCHEN
ENS
BATH
WC
+40 MM
+30 MM
TARNEIT 11-1102
B: 09.2009
I: 07.2011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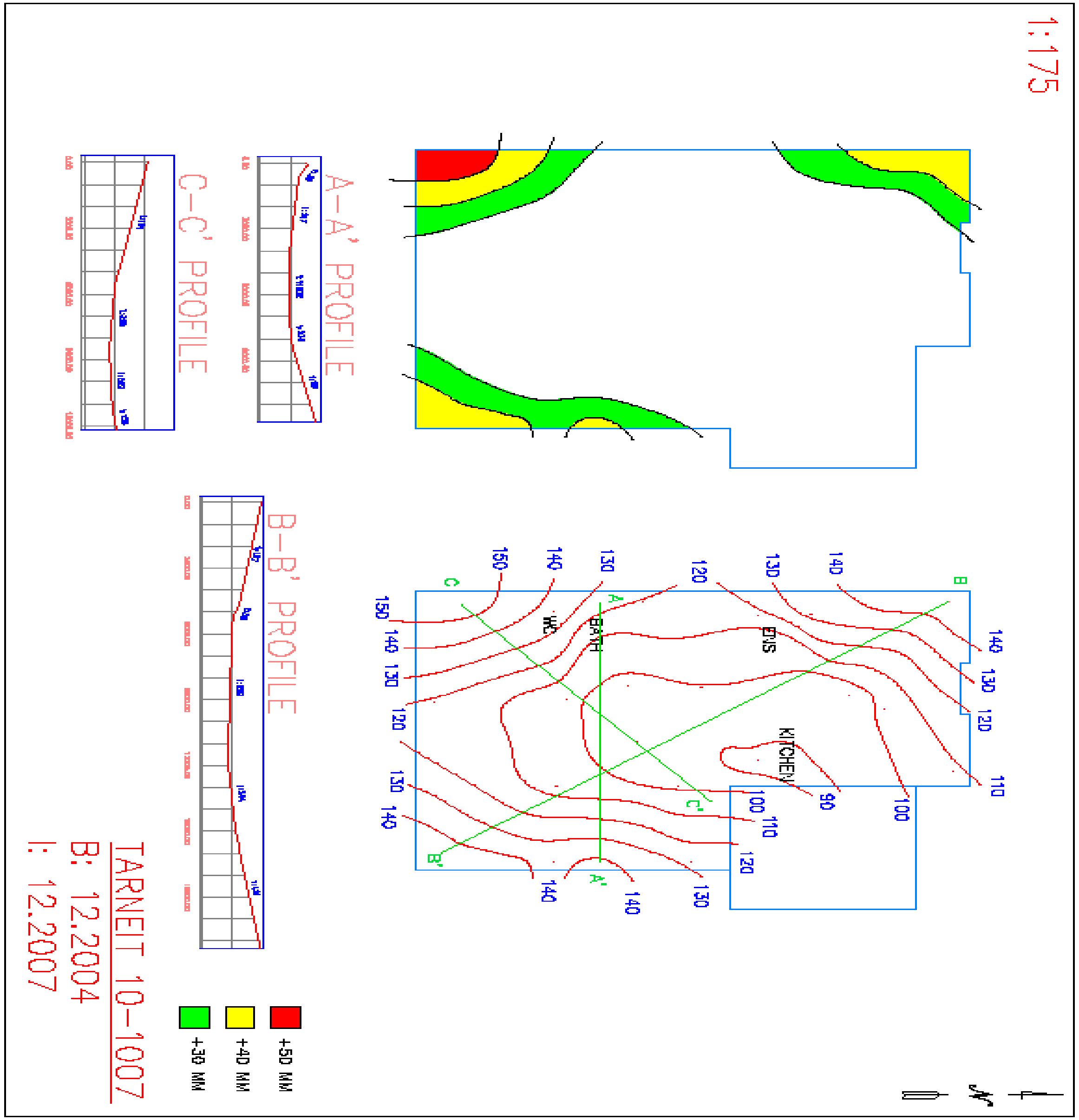
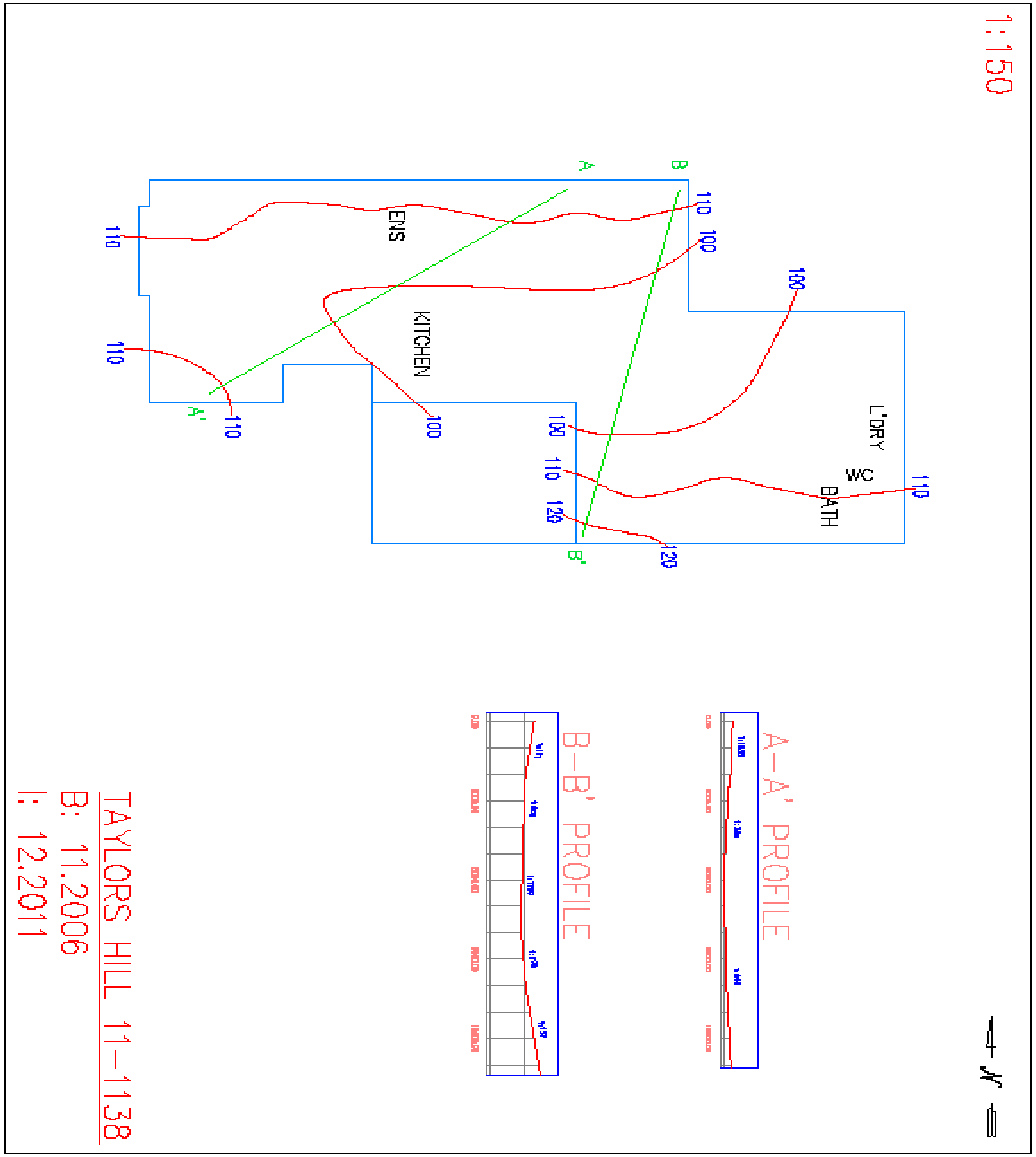
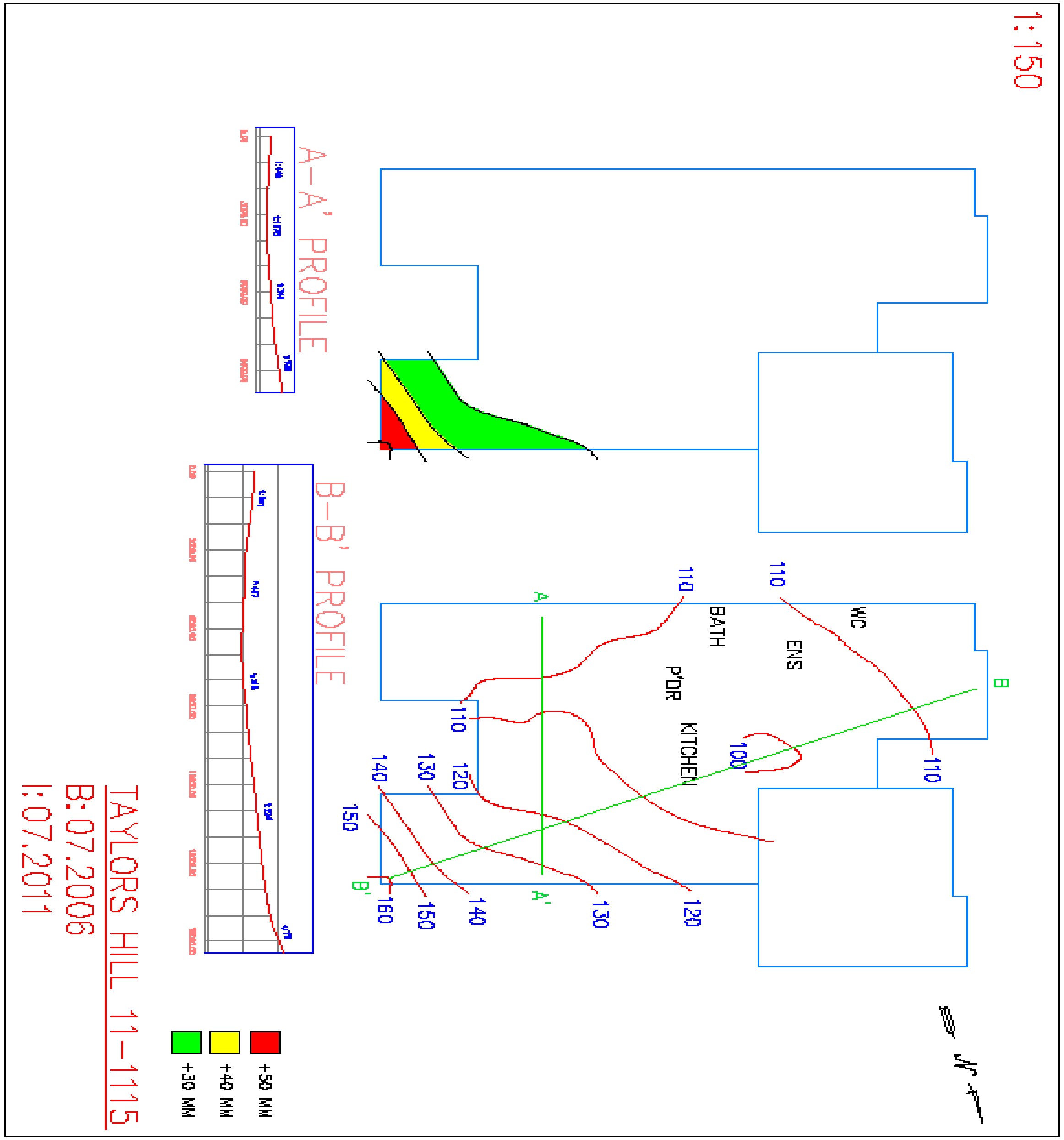
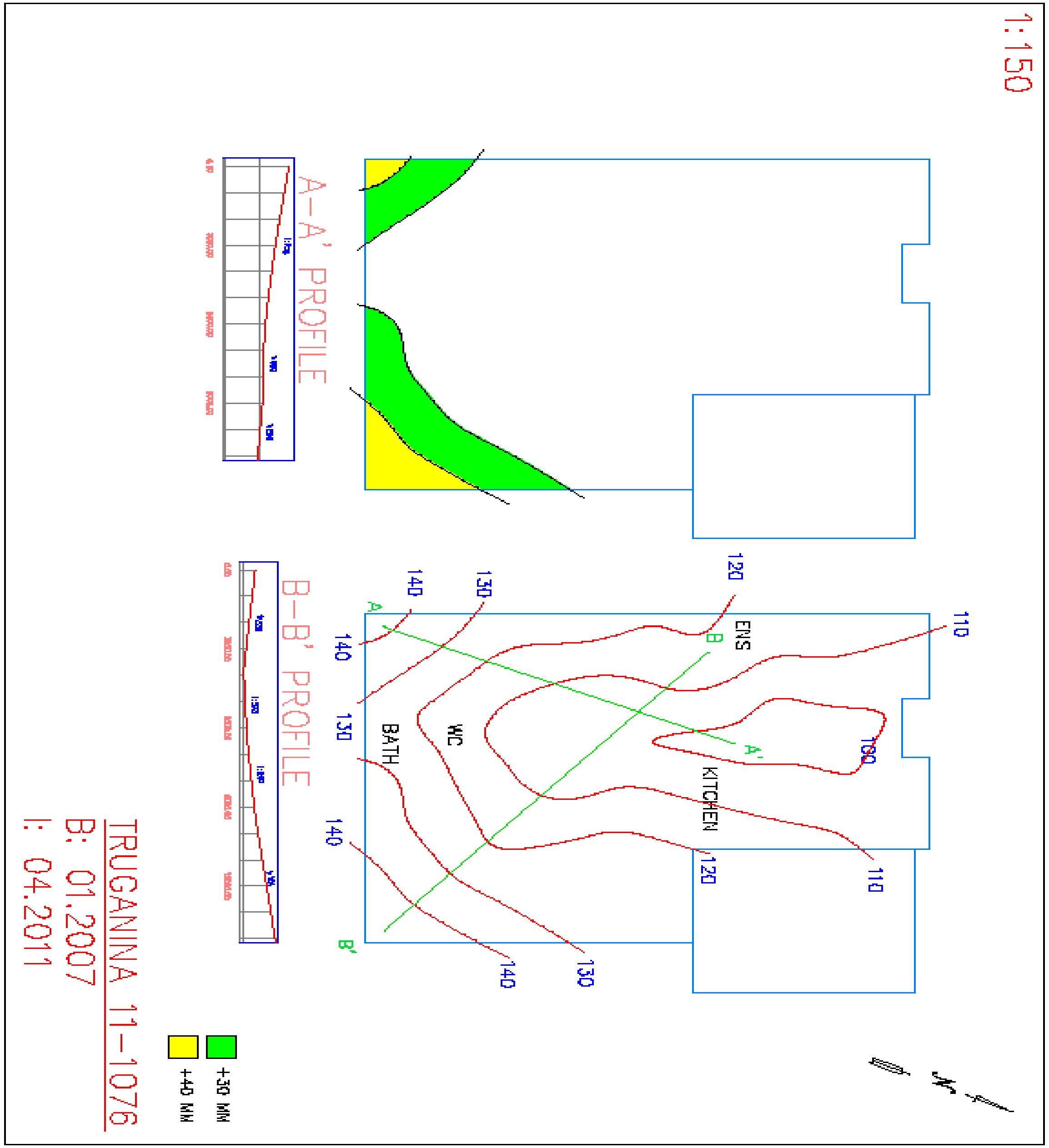
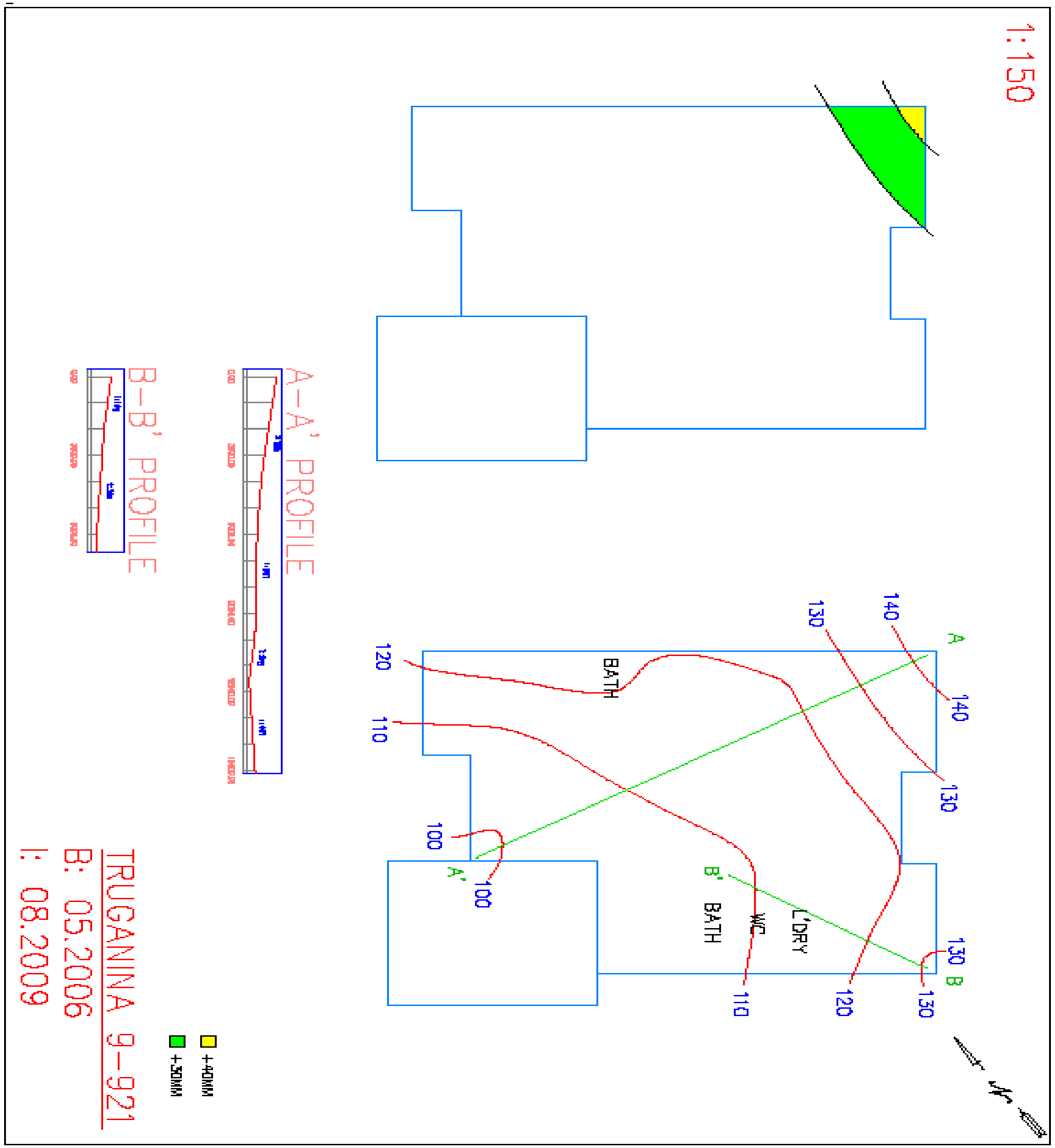
B–B' PROFILE
WC
BATH
BATH
KITCHEN
L'DRY
120
110
100
A
A'
B
B'
TARNEIT 11–1128
B: 11.2009
I: 11.2011

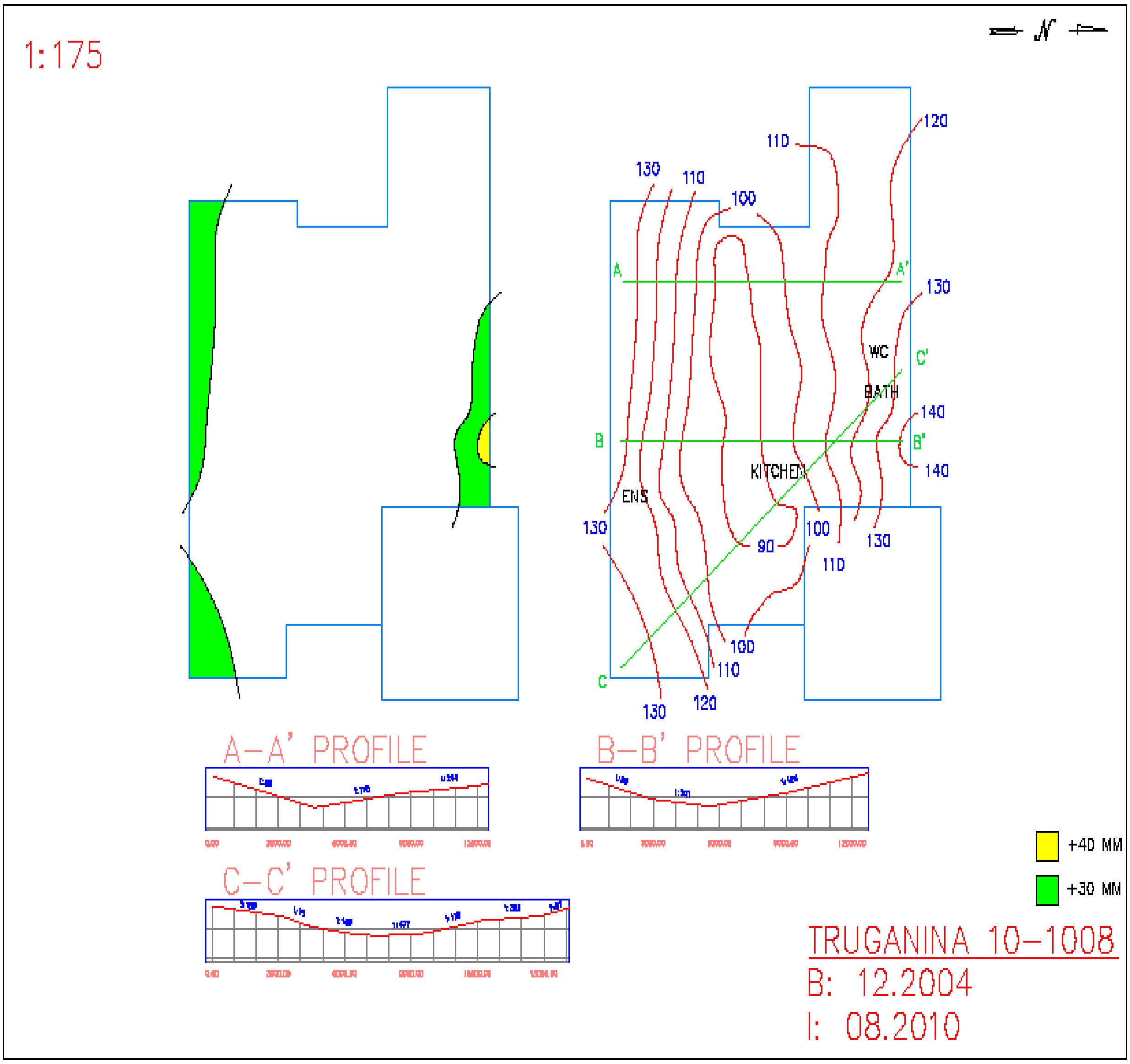

1:175
A-A' PROFILE
B-B' PROFILE
C-C' PROFILE
KITCHEN
BATH
WC
+50 MM
+40 MM
+30 MM
TARNEIT 10-1007
B: 12.2004
I: 12.2007

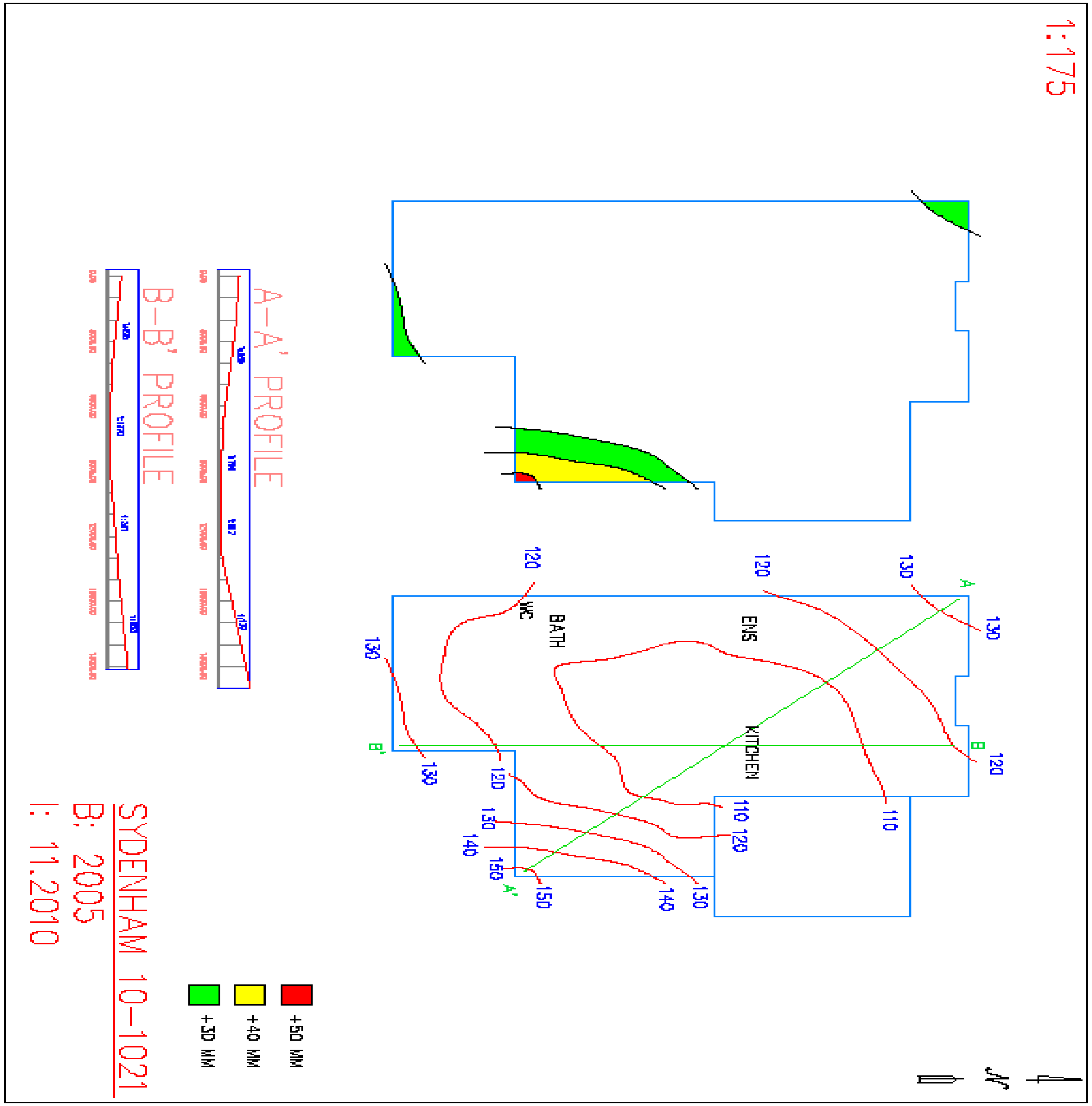

1:150
TAYLORS HILL 11-1138
B: 11.2006
I: 12.2011
A-A' PROFILE
B-B' PROFILE
ENS
KITCHEN
L'DRY
WC
BATH
A
A'
B
B'
110
100
120

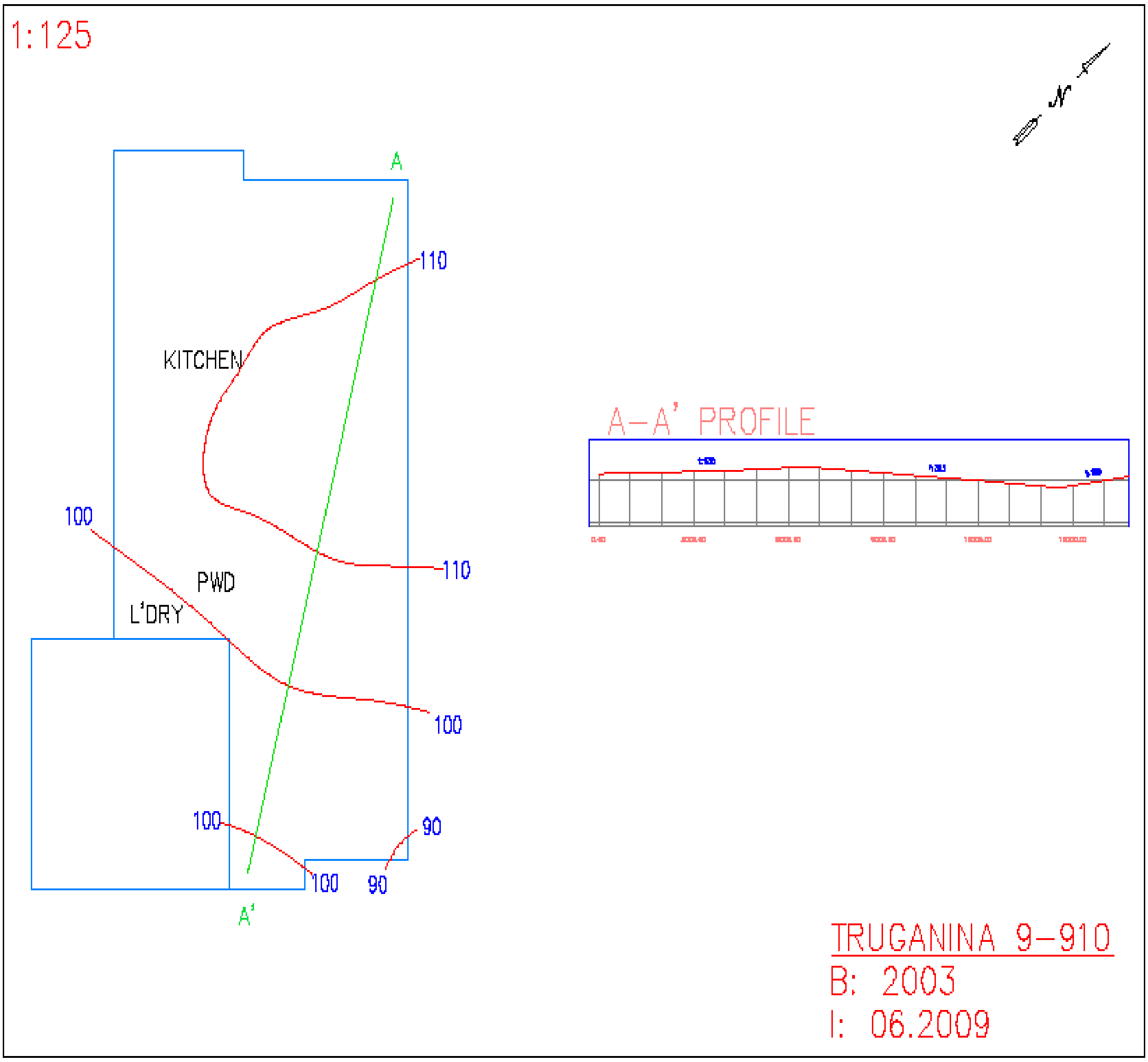

1:150
A-A' PROFILE
B-B' PROFILE
BATH
WC
ENS
P'DR
KITCHEN
TAYLORS HILL 11-1115
B:07.2006
I:07.2011
+50 MM
+40 MM
+30 MM

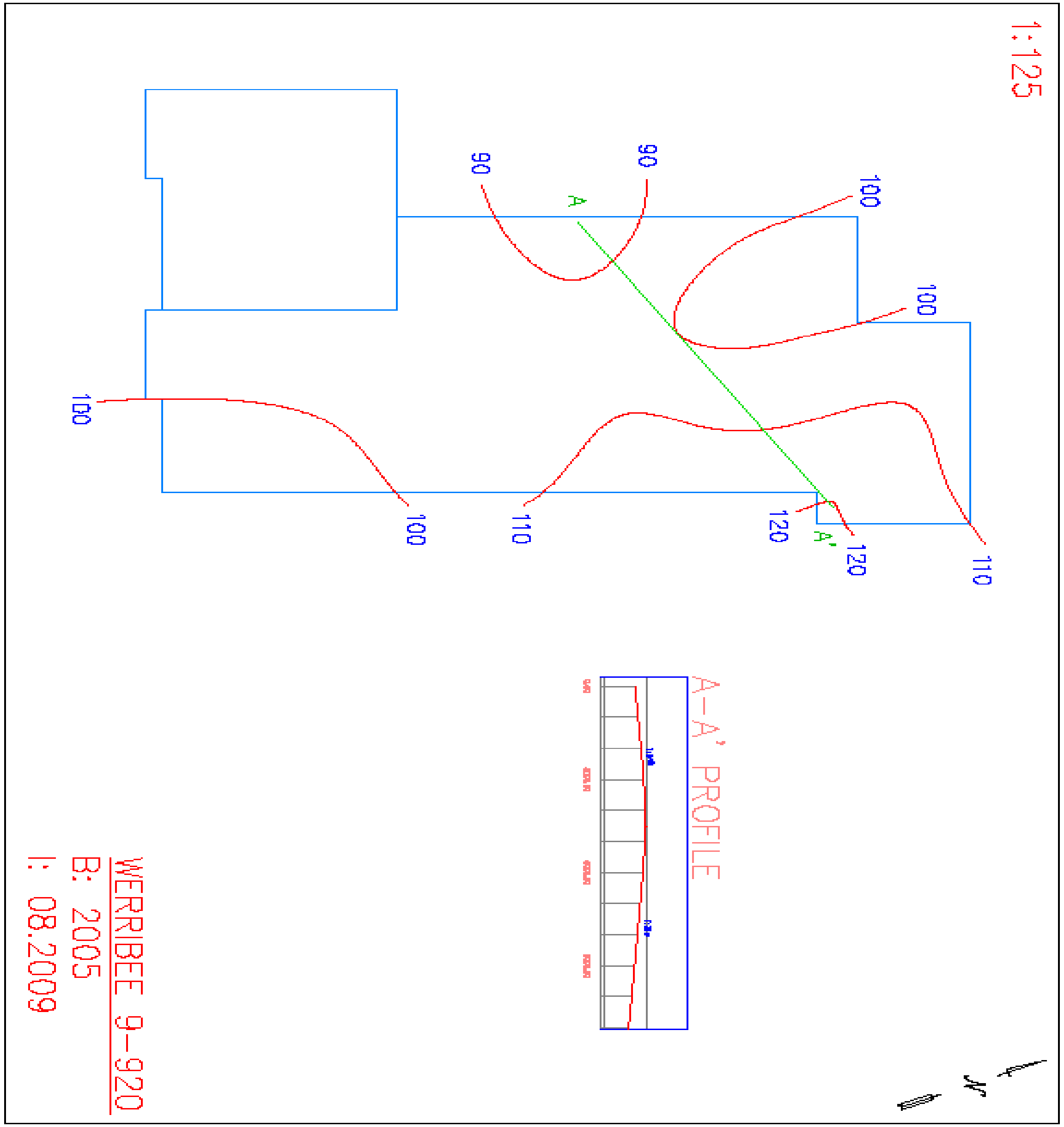

1:150
A–A' PROFILE
B–B' PROFILE
ENS
WC
BATH
KITCHEN
110
120
130
140
100
+30 MM
+40 MM
TRUGANINA 11–1076
B: 01.2007
I: 04.2011

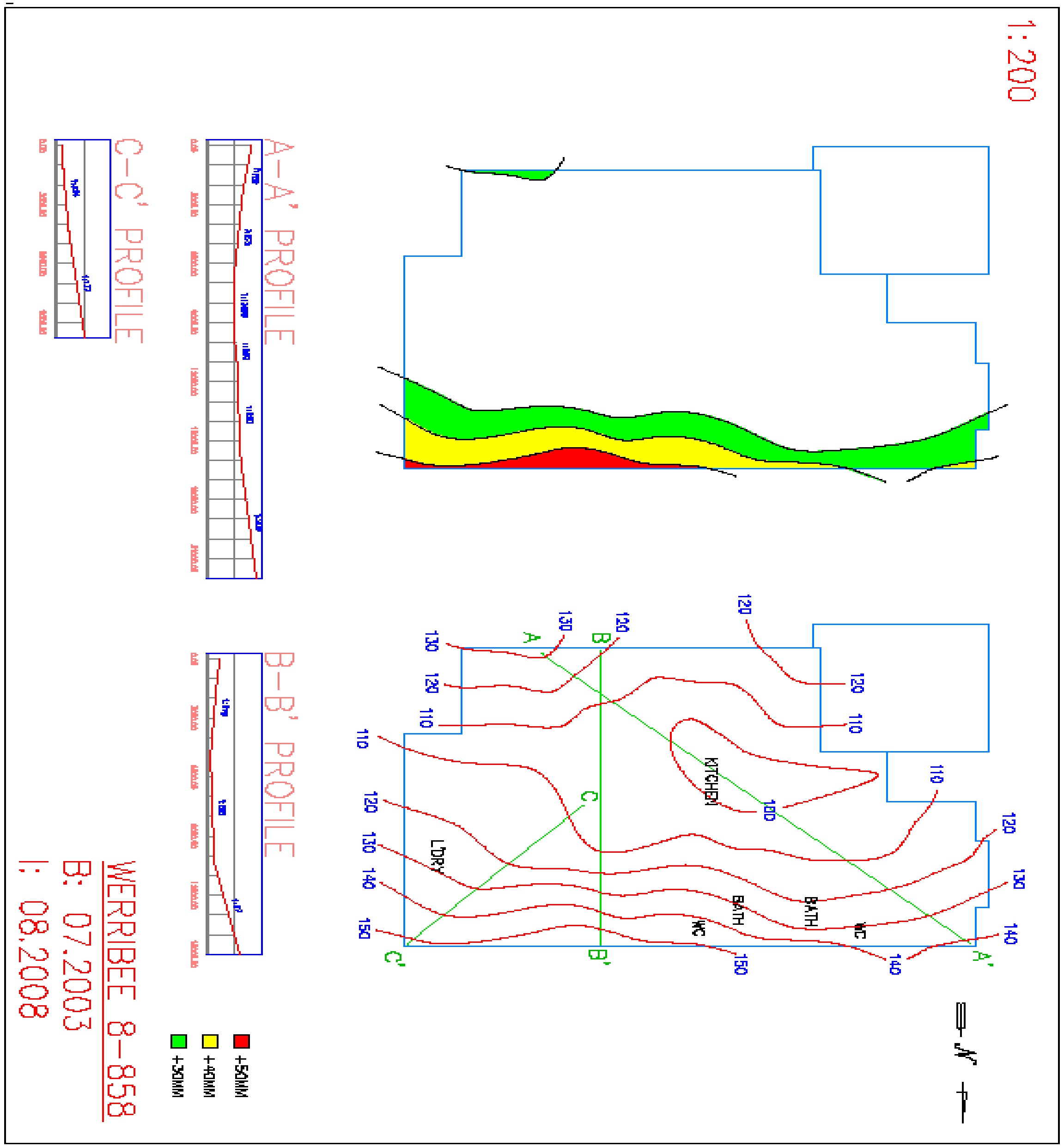

1:150
A–A' PROFILE
B–B' PROFILE
TRUGANINA 9–921
B: 05.2006
I: 08.2009
+40MM
+50MM
BATH
WC
L'DRY
BATH
A
A'
B
B'
100
110
120
130
140

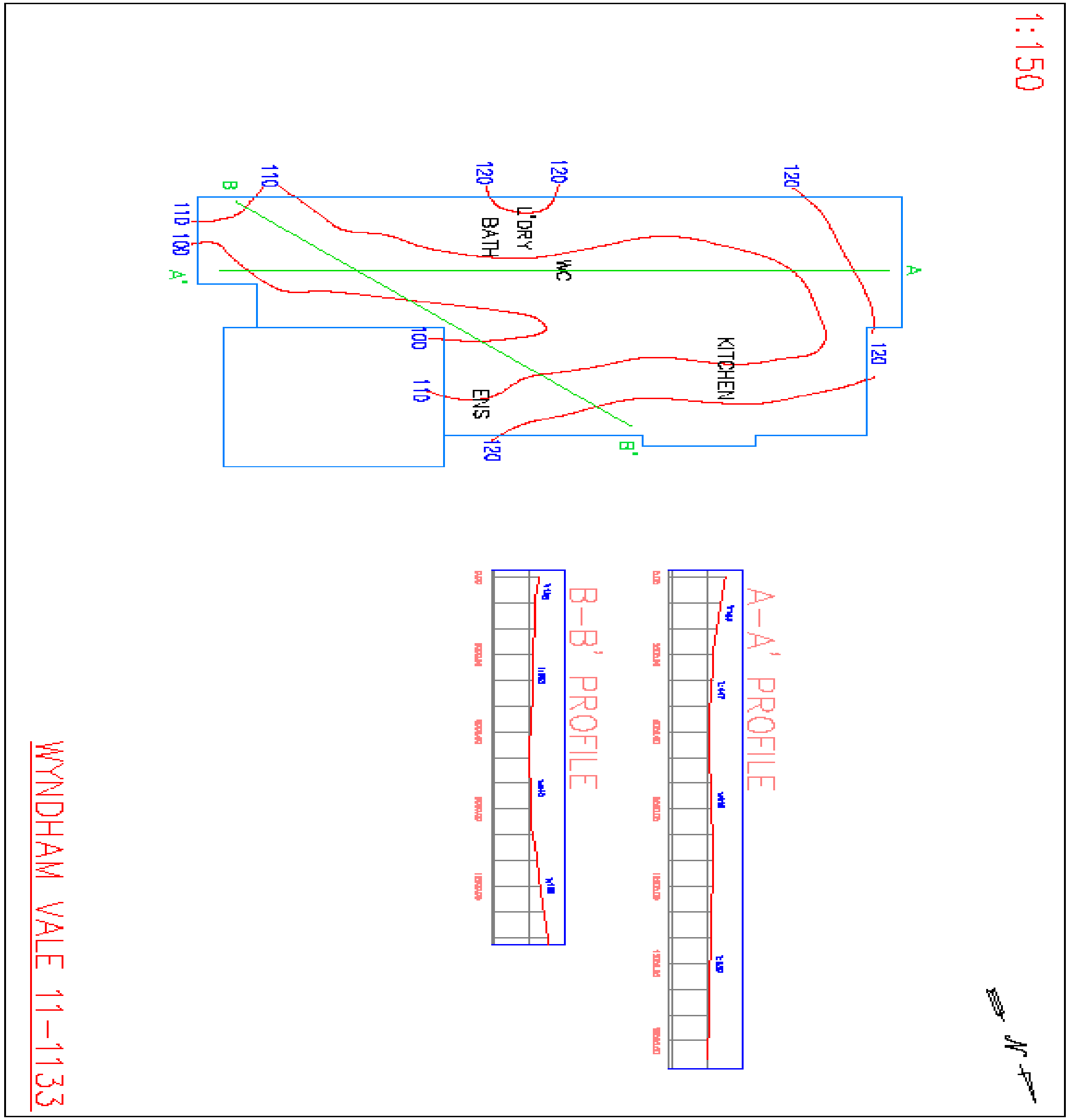

1:175
N
130
110
100
110
120
A
A'
130
WC
C'
BATH
140
B
B'
140
KITCHEN
ENS
130
90
100
130
110
100
110
C
130
120
A–A' PROFILE
B–B' PROFILE
C–C' PROFILE
+40 MM
+30 MM
TRUGANINA 10–1008
B: 12.2004
I: 08.2010

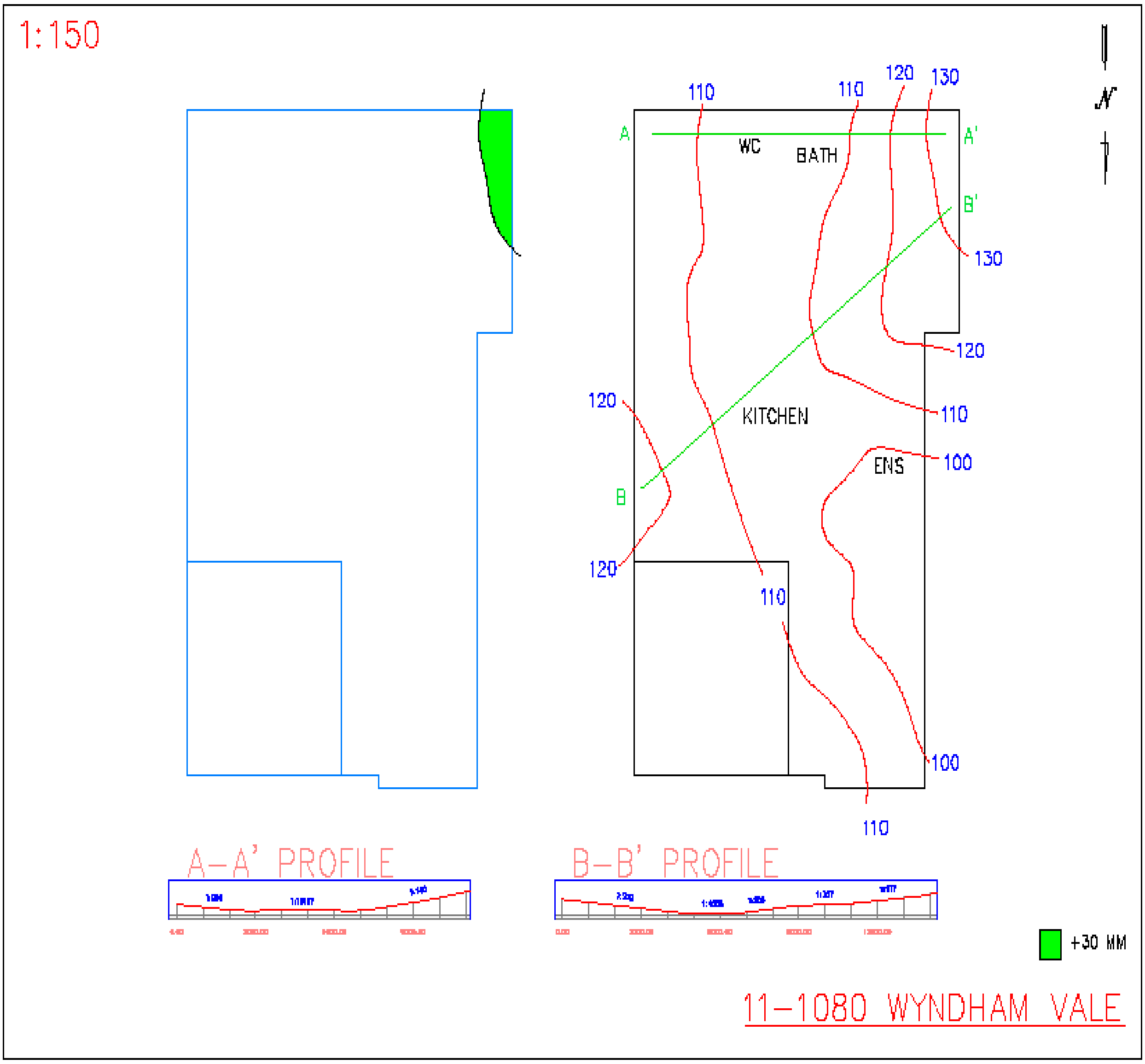

1:175
WC
BATH
ENS
KITCHEN
A-A' PROFILE
B-B' PROFILE
+50 MM
+40 MM
+30 MM
SYDENHAM 10-1021
B: 2005
I: 11.2010


1:125
A
110
KITCHEN
A–A' PROFILE
100
110
PWD
L'DRY
100
100
90
100
90
A'
TRUGANINA 9–910
B: 2003
I: 06.2009


1:125
90
90
A
100
100
100
100
110
120
A'
120
110
A-A' PROFILE
WERRIBEE 9-920
B: 2005
I: 08.2009


1:200
A-A' PROFILE
C-C' PROFILE
B-B' PROFILE
KITCHEN
LDRY
BATH
WC
+50MM
+40MM
+30MM
WERRIBEE 8-858
B: 07.2003
I: 08.2008


1:150
L'DRY
BATH
WC
KITCHEN
ENS
A-A' PROFILE
B-B' PROFILE
WYNDHAM VALE 11-1133



1:150
N
A
A'
B
B'
WC
BATH
KITCHEN
ENS
110
110
120
130
130
120
110
100
120
120
110
100
110
A–A' PROFILE
B–B' PROFILE
+30 MM
11–1080 WYNDHAM VALE

APPENDIX 3

FIELD MOISTURE RESULTS

887 samples were collected by 'R. I. Brown', 'USL Group', 'JM Fieldwork' at 300-700 mm and tested for gravimetric moisture. Results from sites with the following conditions and from samples described as No 4, 5, & 9 were not used.

1. Free surface water near test hole(s).
2. Recent heavily watered nearby ground.
3. Nearby pipe leak detected.
4. Samples taken at depths >700 mm.
5. Having substantial calcrete content.
6. Recent heavy rain.
7. Poor drainage around sample point.
8. Densely populated older developments.
9. Soil fill or with multiple roots.

*After removing these samples 267 remained and were plotted in chapter 5, figure 50.

Table 31: Av. 'GW' in climate periods.

Mean "drought" moisture	17.4%
Mean "transitional" moisture	25.6%
Mean "wet" moisture"	36.4%

The term 'Transitional' describes the short period between the 'Wet' and 'El Nino' (2012-2014). This period followed a record wet 2 year period, therefore the soil moisture at sampling stage may still have been under the influence of the deeper and wetter clays.

Values marked with an asterisk were not used since they were outside the upper and lower 90 percentile limit.

Suburb	Drought	Wet	Transitional
Altona Meadows		37	
Altona North		34	
Altona North			25
Altona North		31	
Altona North	8*		
Altona North	14		
Altona North	11*		
Altona North		30	
Altona North		33	
Altona North		32	
Altona North	14		
Altona North	13		
Altona North	15		
Altona North	16		
Altona North	18		
Bacchus Marsh	17		
Bacchus Marsh	11*		
Bacchus Marsh	8*		
Bacchus Marsh	14		
Bacchus Marsh		27	
Bacchus Marsh			24
Bacchus Marsh			22
Bacchus Marsh		33	
Bacchus Marsh		33	
Bacchus Marsh		31	
Bacchus Marsh		34	
Bacchus Marsh		35	
Bacchus Marsh		35	
Bacchus Marsh		28	
Bacchus Marsh		35	
Bacchus Marsh		35	
Bacchus Marsh		35	
Bacchus Marsh		39	
Braybrook			25
Brookfield		28	
Brookfield		35	
Brookfield		35	
Brookfield		39	
Brookfield		35	
Brookfield			23
Brookfield			26
Brookfield			26
Brooklyn	18		
Burnside	16		
Burnside Heights		37	
Burnside Heights		39	
Burnside Heights		37	
Cairnlea		30	
Cairnlea		29	
Cairnlea	18		
Cairnlea		30	
Cairnlea		36	
Cairnlea		36	
Cairnlea		36	
Cairnlea		42*	
Cairnlea		31	
Cairnlea		39	
Cairnlea		26	
Cairnlea		26	
Cairnlea	18		
Cairnlea		38	

Cairnlea		37	
Caroline Springs			24
Caroline Springs	14		
Caroline Springs	18		
Caroline Springs			28
Caroline Springs			28
Caroline Springs		30	
Caroline Springs		29	
Caroline Springs			29
Caroline Springs		36	
Craigieburn		32	
Craigieburn		35	
Craigieburn	10*		
Craigieburn		32	
Craigieburn		37	
Craigieburn		35	
Craigieburn			24
Craigieburn			23
Derrimut		30	
Derrimut		33	
Eynesbury			30
Eynesbury			28
Eynesbury			26
Eynesbury			30
Eynesbury			26
Gisborne	18		
Gisborne	19		
Gisborne	18		
Gisborne		42*	
Gisborne		39	
Gisborne		38	
Gisborne		36	
Gisborne		33	
Gisborne		41	
Gisborne		31	
Gisborne		33	
Gisborne		38	
Gisborne		33	
Gisborne		38	
Gisborne		32	
Gisborne		37	
Gisborne		33	
Gisborne		38	
Gisborne		33	
Gisborne		38	
Gisborne New	17		
Gisborne New	10*		
Gisborne New	8*		
Gisborne New		39	
Gisborne South	11*		
Gisborne South	10*		
Hillside		37	
Hillside			26
Hillside		36	
Hillside		37	
Hillside		40	
Hillside	18		
Hillside			27
Kurunjang	18		
Kurunjang	19		
Lalor	18		
Lalor	17		
Lalor			30
Melton		35	
Melton	14		
Melton			28
Melton	14		
Melton	20		
Melton	17		
Melton			24
Melton	11*		
Melton	12		
Melton South	14		
Melton West		37	
Melton West		35	
Melton West		34	
Melton West		36	
Melton West		39	
Melton West		31	
Melton West		24	
Melton West			26
Melton West		40	
Melton West		37	
Melton West		39	
Melton West		32	
Niddrie		39	
Niddrie		37	
Plumpton		36	
Plumpton		30	
Plumpton		39	
Plumpton		40	
Plumpton		38	
Plumpton		32	
Pt Cook		33	
Pt Cook		35	
Pt Cook		35	
Pt Cook		37	
Pt Cook		33	
Pt Cook		32	
Pt Cook		34	
Pt Cook		35	
Pt Cook		33	
Pt Cook		35	
Spotswood			30
Spotswood			26
Spotswood		40	
St Albans		37	
St Albans		31	
St Albans		33	
St Albans		36	
St Albans		38	
Tarneit		37	
Tarneit		39	
Tarneit		40	
Tarneit		39	
Tarneit		38	

Tarneit		31	
Tarneit		35	
Tarneit		33	
Tarneit		37	
Tarneit		36	
Tarneit		35	
Tarneit	21		
Tarneit		37	
Tarneit		42*	
Tarneit		34	
Tarneit		37	
Taylors Hill		36	
Taylors Hill		39	
Taylors Hill		40	
Taylors Hill		34	
Taylors Hill		34	
Taylors Hill		39	
Taylors Hill	19		
Taylors Hill		42*	
Taylors Hill		38	
Taylors Hill		38	
Taylors Hill		42*	
Taylors Hill		32	
Taylors Hill		33	
Taylors Hill		36	
Taylors Lakes		36	
Taylors Lakes		38	
Truganina		42*	
Truganina		40	
Truganina		41	
Truganina		42*	
Truganina		34	
Truganina		37	
Truganina		40	
Truganina		37	
Truganina		39	
Truganina		29	
Truganina	21		
Truganina	22		
Truganina	19		
Truganina	22		
Werribee		35	
Werribee		39	
Werribee	15		
Werribee		37	
Werribee		38	
Williamstown		40	
Williamstown	13		
Williamstown		36	
Williamstown	16	34	
Williamstown		32	
Williamstown		33	
Williamstown		39	
Williamstown		33	
Williamstown	14		
Williamstown	16		
Williamstown	20		
Williamstown			24
Williamstown	14		
Williamstown		32	
Williamstown			25
Williamstown			22
Williamstown			22
Williamstown	16		
Williamstown			23
Williamstown			27
Wyndham Vale		34	
Wyndham Vale		33	
Wyndham Vale		35	
Wyndham Vale			22
Wyndham Vale		40	
Wyndham Vale		34	
Wyndham Vale		41	
Wyndham Vale			29
Wyndham Vale		39	
Wyndham Vale		41	
Wyndham Vale			22
Wyndham Vale		40	
Wyndham Vale		34	
Wyndham Vale		39	
Wyndham Vale		41	
Wyndham Vale			21
Wyndham Vale		41	
Wyndham Vale		42*	
Wyndham Vale		33	
Wyndham Vale		39	
Wyndham Vale		42*	
Wyndham Vale		31	
Yarraville	16		
Yarraville	20		
Yarraville	19		

APPENDIX 4

CONDITIONED" CORE SHRINKAGE TEST (CCS)

The aim of the new CCS test was to eliminate as many of the variable parameters as possible to allow standardisation and comparison of soil indices. The 3 most common tests in AS1289 were considered.

- Shrink/Swell,
- Loaded Core Shrinkage.
- Unloaded Core Shrinkage.

Most geotechnical practitioners are familiar with these tests and the author considered it an advantage to develop one of these tests with similar parameters with some improvements. The most important being a consistent suction and moisture starting point for the test.

Prior to choosing the test method a number of experiments were carried out testing moisture conditioning apparatus. Sample preparation was also attempted by compacting disturbed samples by the normal compaction method and by compacting clay clods, however, none of the methods achieved the aims of this thesis. The soil fabric and behaviour was different to the undisturbed samples even at the same moisture and density. Once it was decided to use Shelby 38 mm ø tubes to collect relatively undisturbed samples the basic test method chosen was similar to the unloaded core shrinkage test in AS1289.

Ideally soil laboratory tests should be simple and inexpensive and whenever possible give repeatable and comparable results which consistently represent the behaviour of the soil parameters being investigated. In residential construction, complicated test requiring long testing procedures and expensive equipment and facilities can rarely be carried out within the time and cost restraints imposed by the industry; therefore it was decided that a shrink test was best to determine a 'soil index' suitable to calculate the range of foundation movements likely in expansive clays. This shrink test was similar to the unloaded core shrinkage test with some important modifications to make it speedier, more accurate and more efficient.

A type of shrink/swell test which did not require soil suction readings was first introduced to the industry by Colin Thorne in 1984 and has since been used for many years in Australia was not used in this research due to a number of factors.

- The swell portion of the test is time consuming and requires two correction factors due to the lack of suction readings and to resolve the effect of the two dimensional sample confinement during the swelling process.
- The need for 50 mm diameter disturbed samples makes it often difficult to sample highly expansive clays in dry soil conditions with small drilling rigs often needed for working in small allotments or existing old houses.
- The final result (I_{ss}) is reliant on the initial soil moisture.
- The shrink and swell paths are not the same and make it difficult to reconcile the two test types. (Refer chapter 2)

Nowadays psychrometers are more readily available, cheaper, easier to use and more accurate within the suction ranges required in expansive clays and Australian conditions.

After a long experimental stage it was decided to condition an 'identical' pair of samples by wrapping each with 2 layers of thin but dense kitchen sponges and held tightly within split brass tubes. They were then placed in pairs in small containers filled with de-ionised water until the preferred suction was achieved. This method only allowed a small amount of lateral swell. To avoid the problem of linear versus lateral swell however it was soon decided to remove the brass split tubes. These tubes were then only used to hold the samples during trimming and cutting thin slices to test in the psychrometer.

In order to have samples A and B always at the same condition during the shrink testing and the cutting of the suction samples, they were wrapped with slightly moist kitchen sponges to prevented cracking and stored next to each other in similar room temperature. Sample 'A' to shrink and 'B' to achieve the suction intervals required. The shrinking process was carried out at room temperature with both samples. On completion of each reading they were re-wrapped in slightly moist clean sponge again to continue the shrink test and suction readings. The whole of sample (A) was used to measure shrinkage and gravimetric moisture loss and at the same time a

≈5 mm thick slice from sample (B) was used to test suction. This process was carried out 3 times at the range of suctions chosen and finally sample (A) was allowed to oven-dry at 105° C overnight, then weighed and its length measured. Suction was not measured at this point but a 7pF value was assumed at oven-dry moisture. (Some researchers quote this suction sign post as 6.8pF however the graphs below show that this makes little difference to the results since at >6pF there is very little further shrinkage)

The graphs were limited to 4 points and the resultant trend-line was drawn by using Microsoft polynomial order 3 or 4 to achieve a line of 'best-fit'. It was found that the shape of the curves differed even in samples with similar final shrinkage. The author suggests that in the research area the cations such as Ca, Mg and Fe, which are common in this soil type, may play a part in the shrinking and swelling processes of the clay structure.

For plotting the CCS and SWC curves the following procedure was followed:

1. The first suction, sample length and weight was measured in the fully conditioned state (3-3.5pF); the second readings at 3.5-4.5pF and the third 4-5-5pF.

2 To create the 4th point and an almost horizontal linear end of the curve the suction/shrink data points at 7.5, 8, 8.5 and 9 pF were included in the graph with a zero shrink. After creating the trend-line, the graph was trimmed to a maximum suction of 7pF.

3 The Microsoft Excel Exponential trend-line was used for the SWCC graphs which ended at 7pF and, where necessary, was extended down to 3pF suction values using the 'predictor' in the program. (This predictor was only used for very small extensions of the curves). The graphical plots were used to calculate and compare I_{ccs} values by using the current AS2870 models with modifications as shown in chapter 7.

4 The SWCC graphical plots from the Conditioned Core Shrinkage tests were used to compare surface suction variations (Δu_s) during the climatic condition in the research

period and provide new design parameters for calculating y_s for a greater range of soil suction conditions.

The changes made to the testing procedure reduced the testing time to about 5-7 days (depending on the soil types). This timeline is suitable for normal commercial testing.

The S/S test carried out as per Australian Standards 1289 gives varying results at the different initial moisture sampled. This is clear when one compares the CCS test graphs with equation 3. The steeper trend-lines of the shrink/suction plots shown in appendix 5 provide one explanation for this, thus the conditioned core shrinkage index (I_{ccs}) is higher in wet climate zones than in the dry suction zones in figure 47 shows the different I_{ccs} along the curve. Two straight lines may be used to simplify the Characteristic Ground Movement (y_s) calculation as shown in chapter 7 to represent the variation in the soil indices.

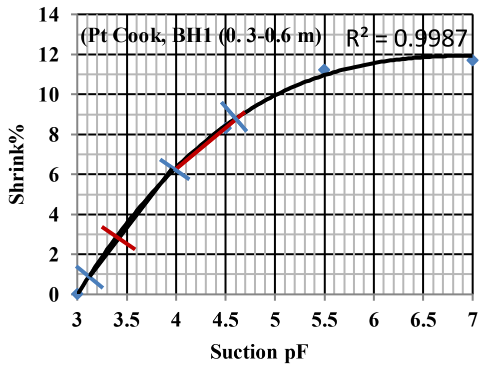
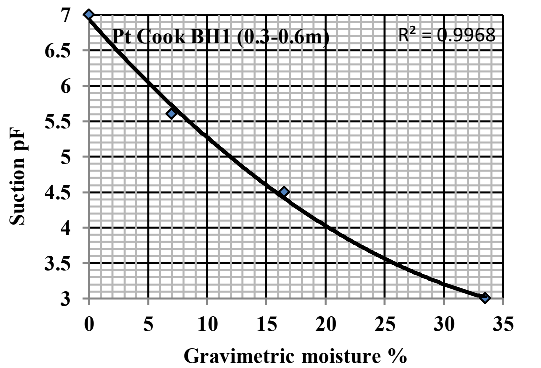
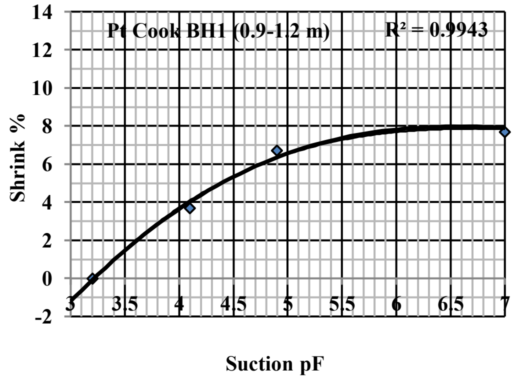
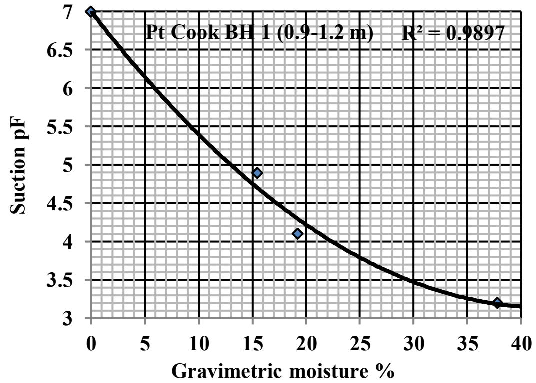
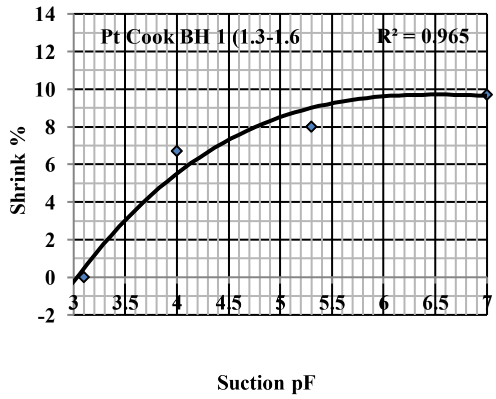
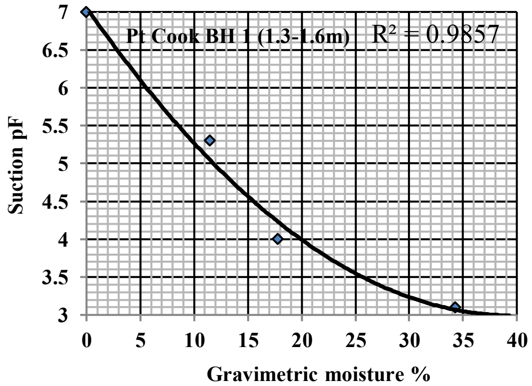
The (CCS) test solves the initial moisture problem and allows the SWC curve to be plotted from the same starting point. The SWCC together with the field soil moistures tested allows a good estimate of the surficial suction values (Δu_s). The CCS and SWCC test results are shown in Appendix 5; both of these plots are a great help in forensic work. One can compare the theoretical slab movement with moisture variation or estimate the slab movement for the past and future based on soil suctions at the time of testing compared with earlier moisture results.

APPENDIX 5

CONDITIONED CORE SHRINKAGE, SUCTION & SWCC.

Note (1) - The colour was described in a moist condition).

Note (2) – y_s has been calculated for 'Normal' Zone 3 and 'Inundated' Zone 3(a) but no fill considered.

<table>
<tr><th>POINT COOK – Suction V Shrink</th><th>POINT COOK – SWCC</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Silty Clay. Colour: Dark-brown.
Δus, 3.4–4.0pF, I_{ccs} = 5.3%, 4.0–4.6pF I_{ccs} = 4.2%
Δus, 3.1–4.0pF, I_{ccs} = 6.0%, 4.0–4.6pF I_{ccs} = 4.2%</td><td>Conditioned moisture C_W = 34%.
Conditioned suction C_S = 3.0pF.</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Silty Clay + calcrete. Colour : Grey/red/brown
Δus, 3.4–4.0pF, I_{ccs} = 4.3%, 4.0–4.6pF I_{ccs} = 3.3%
Δus, 3.1–4.0pF, I_{ccs}= 4.9%, 4.0–4.6pF, I_{ccs} = 3.3%</td><td>Conditioned moisture C_W = 38%.
Conditioned suction Cs = 3.2pF.</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Silty Clay. Colour: Grey/red/brown
Δus, 3.4–4.0pF, I_{ccs} = 5.2%, 4.0–4.6pF I_{ccs} = 3.5%
Δus, 3.1–4.0pF, I_{ccs} = 5.8%, 4.0–4.6pF, I_{ccs} =3.5%</td><td>Conditioned moisture C_W = 34%.
Conditioned suction Cs = 3.1pF.</td></tr>
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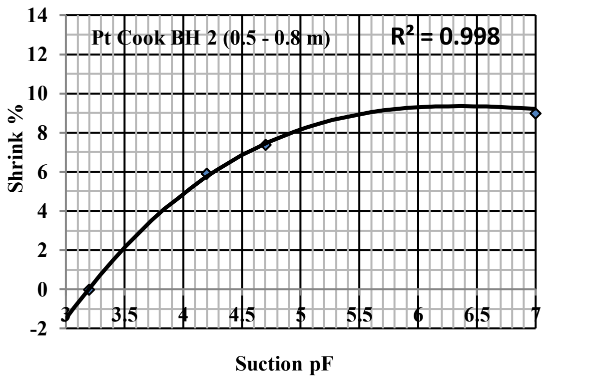
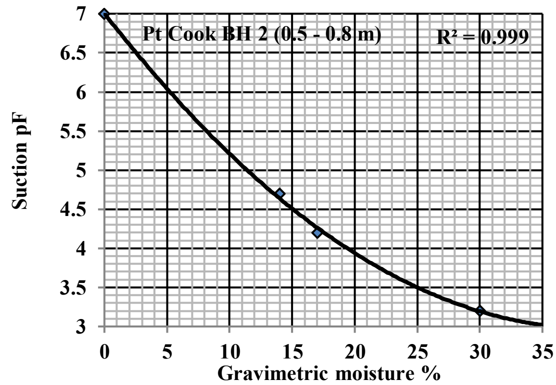
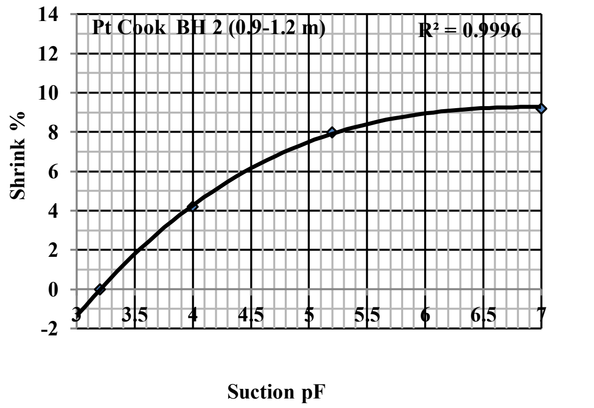
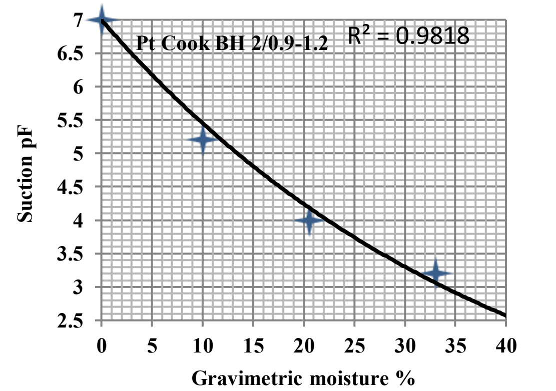




Silty Clay + minor calcrete.
Colour: Grey/red/brown.
Δus 3.4–4.0pF, I_{ccs} = 5.3%, 4.0–4.6pF I_{ccs} = 4.1%
Δus 3.1–4.0pF, I_{ccs} = 6.3%, 4.0–4.6pF, I_{ccs} = 4.1%.

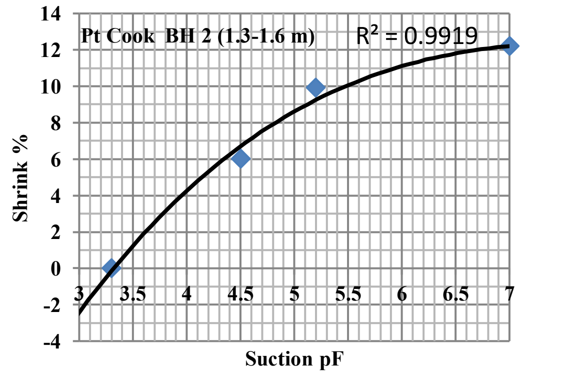
Conditioned moisture C_W = 30%.
Conditioned suction Cs = 3.2pF.

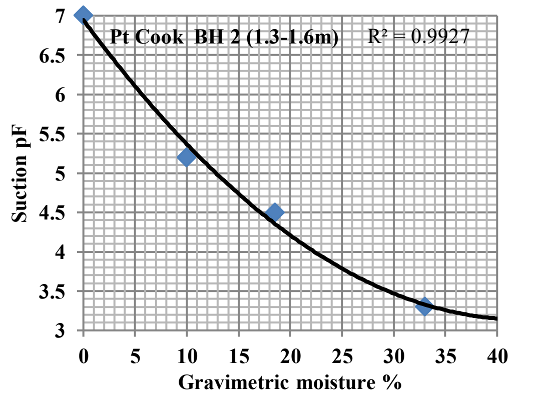




Silty Clay + trace calcrete.
Colour: Grey/orange/brown
Δus = 3.4–4.0pF, I_{ccs} = 5.4%, 4.0–4.6pF, I_{ccs} = 3.7%
Δus = 3.1–4.0pF, I_{ccs} = 6.7%, 4.0–4.6pF, I_{ccs} = 3.7%

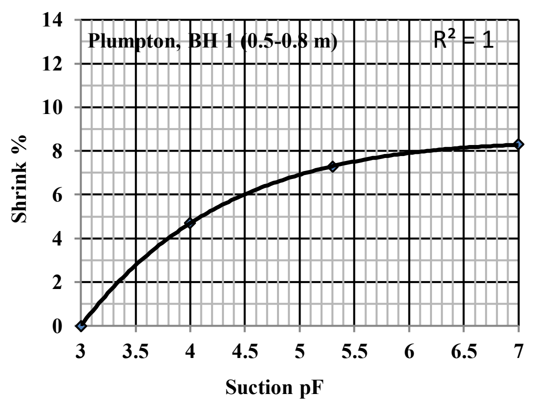
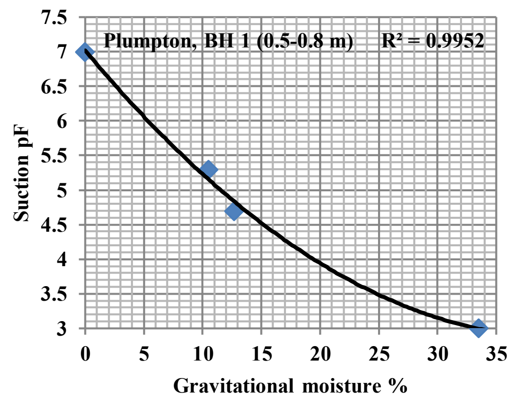
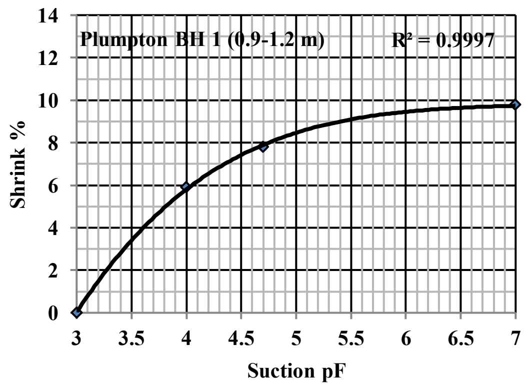
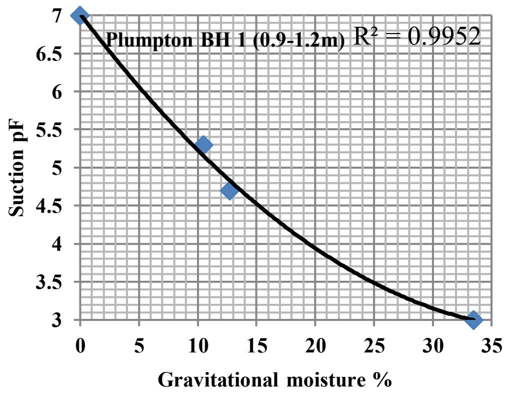
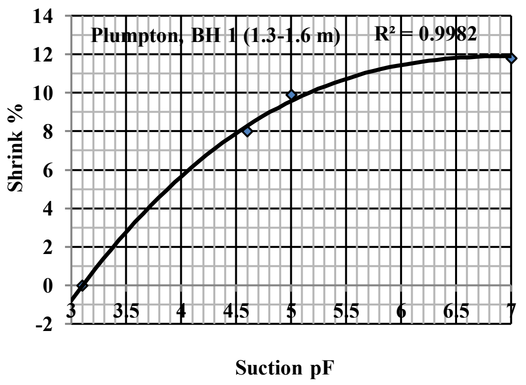
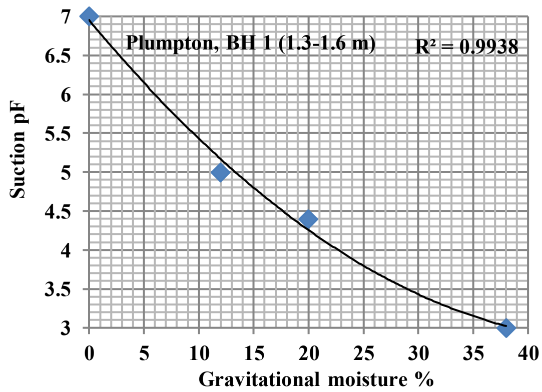
Conditioned moisture C_W = 38%.
Conditioned suction Cs = 3.2pF.

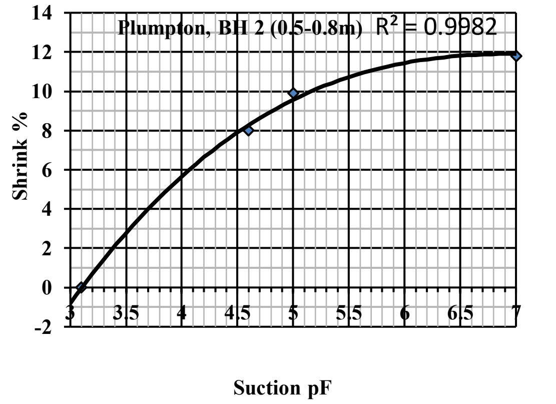


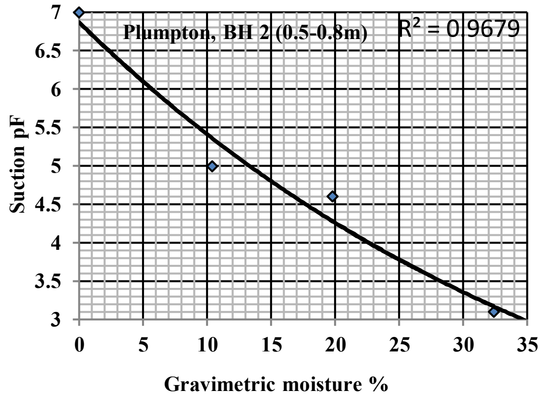


Silty Clay - Colour: Grey/ brown/orange
Δu_s =3.4–4.0pF, I_{ccs} = 6.3%, 4.0–4.6pF, I_{ccs}= 4.7%
Δu_s =3.1–4.0pF, I_{ccs} = 7.3%, 4.0–4.6pF, I_{ccs}= 4.7%

Conditioned moisture C_W = 30%.
Conditioned suction Cs = 3.3pF.

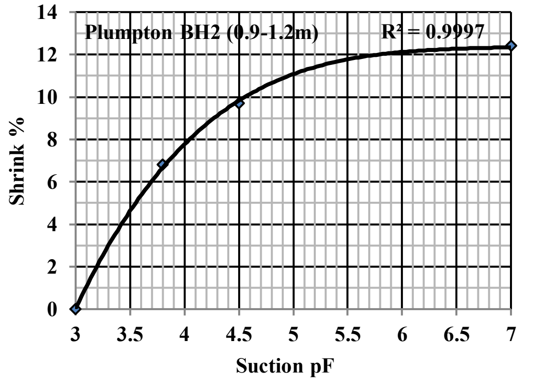
PLUMPTON – Suction V Shrink	**PLUMPTON – SWCC**
	
Silty Clay + calcrete. Colour: Light grey-brown. **Δu_s = 3.1–4.0 pF, I_{ccs} = 4.5%, 4.0–4.6 pF, I_{ccs} = 2.5%**	**Conditioned moisture C_{wn} = 34%.** **Conditioned suction Cs = 3.0 pF.**
	
Silty Clay. Colour: Grey-brown. **Δu_s = 3.1–4.0pF, I_{ccs} = 5.7%. 4.0–4.6pF, I_{ccs} = 3.2%**	**Conditioned moisture C_w = 34%.** **Conditioned suction Cs = 3.2pF.**
	
Silty Clay. Colour: Grey-brown. **Δu_s = 3.1–4.0pF, I_{ccs} = 6.4%. 4.0–4.6pF, I_{ccs} = 4.5%**	**Conditioned moisture C_w = 38%.** **Conditioned suction Cs = 3.1pF.**

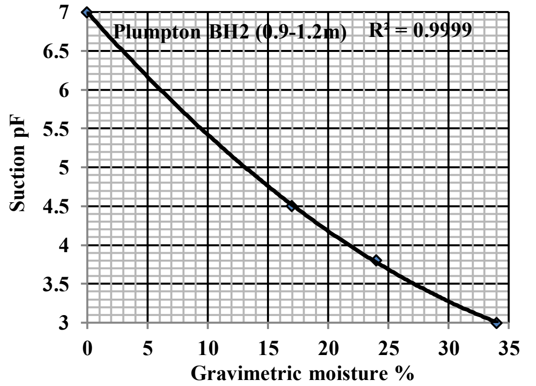




Silty Clay. Colour: Grey-brown.
Δu_s= 3.1–4.0pF, I_{ccs} = 6.6%. 4.0–4.6pF, I_{ccs}= 4.3%

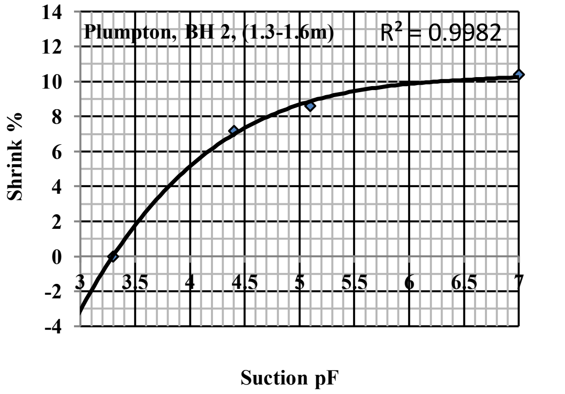
Conditioned moisture Cw = 32.5%.
Conditioned suction Cs =3.1pF.

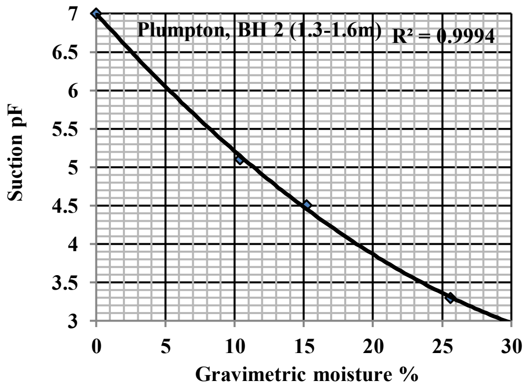




Silty Clay. Colour: Grey-brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 7.4%. 4.0–4.6pF, I_{ccs} = 4.2%

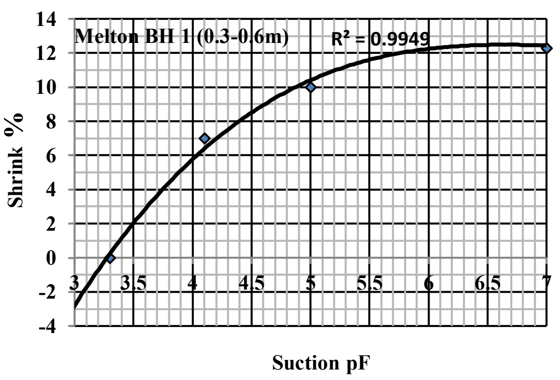
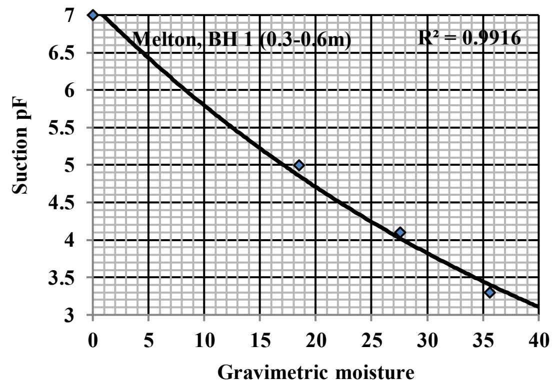
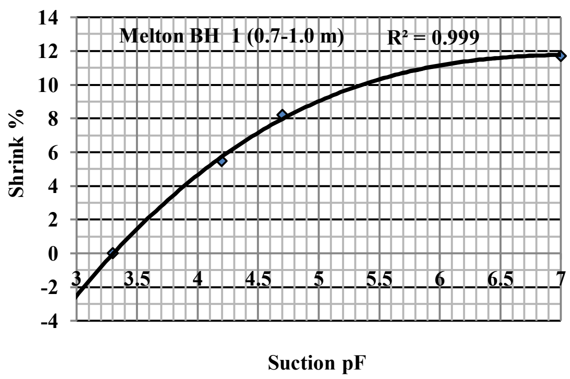
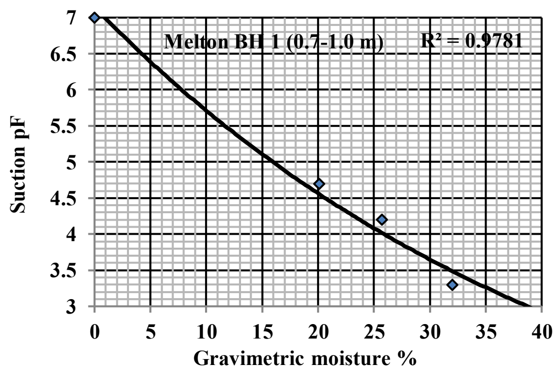
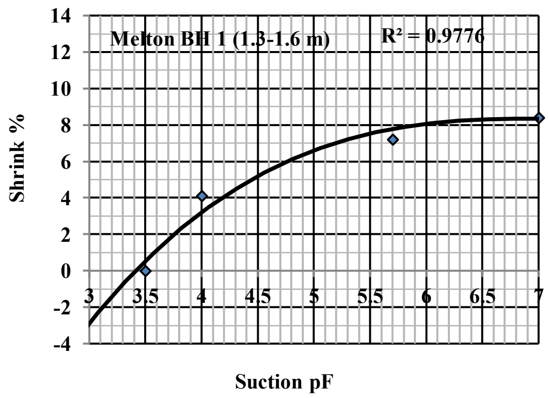
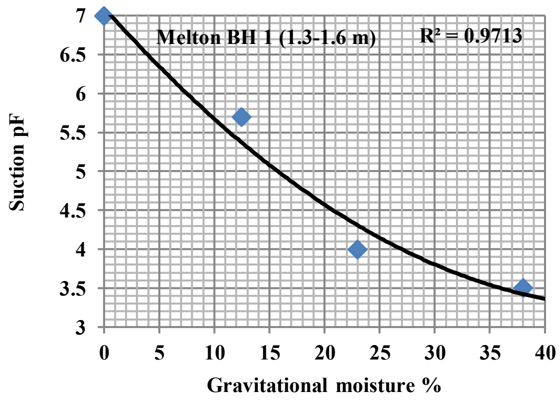
Conditioned moisture Cw = 34%.
Conditioned suction Cs = 3.0pF.

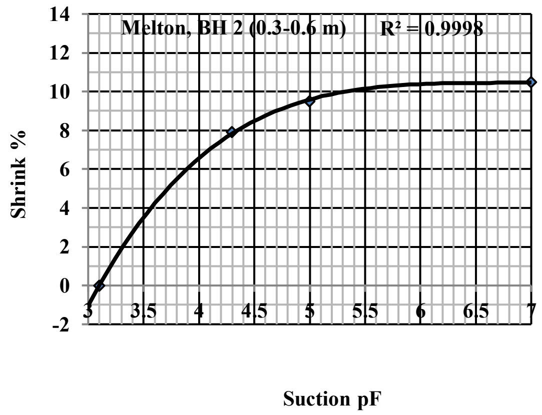


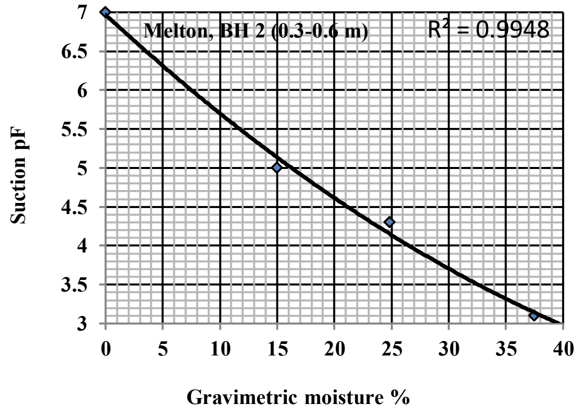


Silty Clay. Colour: Grey-brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 7.9%. 4.0–4.6pF, I_{ccs} = 4.3%

Conditioned moisture Cw = 25.5%.
Conditioned suction Cs = 3.3pF

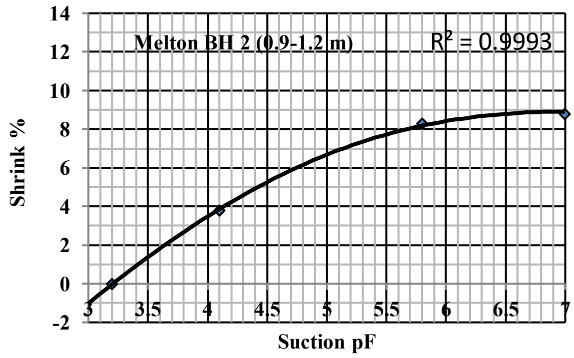
<table>
<tr><td>MELTON – Suction V Shrink</td><td>MELTON – SWCC</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Silty Clay. Colour: Dark-red- brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 8.1%. 4.0–4.6pF, I_{ccs} = 5.3%.</td><td>Conditioned moisture Cw = 35.5%.
Conditioned suction Cs = 3.3pF.</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Silty Clay. Moist colour: Red-orange mottle-brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 6.9%. 4.0–4.6pF, I_{ccs} = 4.9%.</td><td>Conditioned moisture Cw = 32.5%.
Conditioned suction Cs = 3.3pF.</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Silty Clay. Moist colour: Red-orange mottle-brown.
Δu_s = 3.2–4.0pF, I_{ccs} = 6.0%. 4.0–4.7pF, I_{ccs} = 3.9%.</td><td>Conditioned moisture Cw = 38%.
Conditioned suction Cs = 3.5pF.</td></tr>
</table>

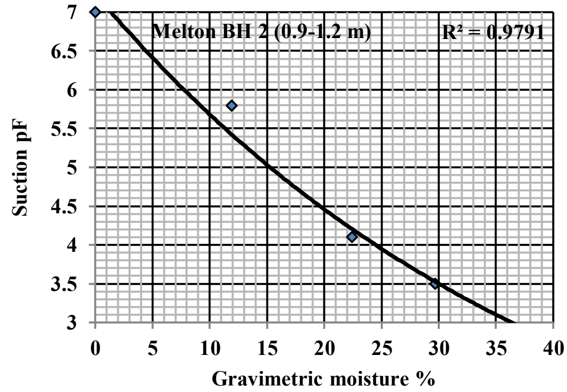




Silty Clay + minor sand. Colour: Light grey-brown.
Δu_s = 3.1-4.0pF, I_{ccs} = 7.0%, 4.0–4.6pF, I_{ccs} = 3.6%.

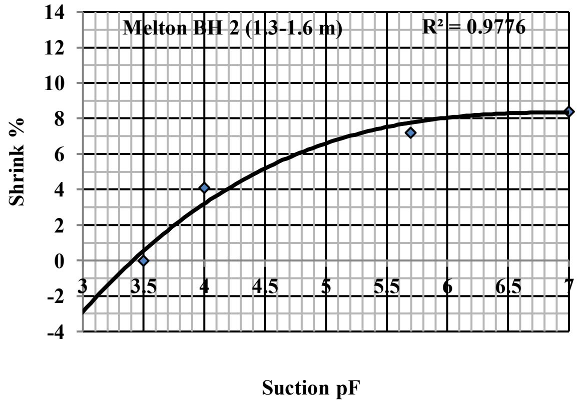
Conditioned moisture C_W = 37.5%.
Conditioned suction Cs = 3.1pF.

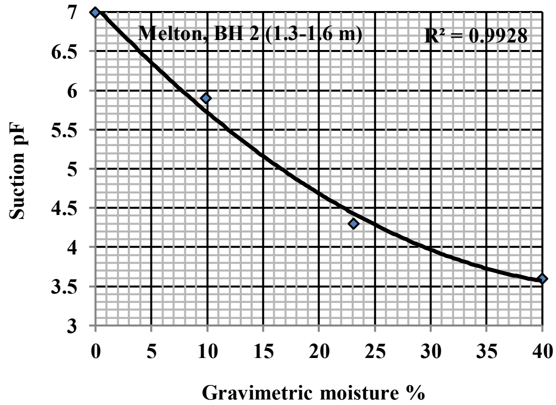




Silty Clay + minor sand. Colour: Light grey-brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 4.4%. 4.0–4.6pF, I_{ccs} = 3.4%.

Conditioned moisture C_W = 30%.
Conditioned suction Cs = 3.5pF.

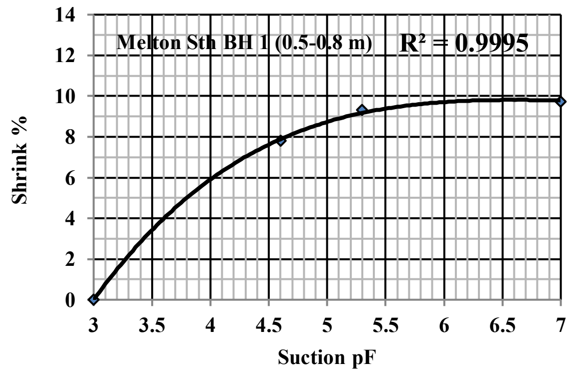


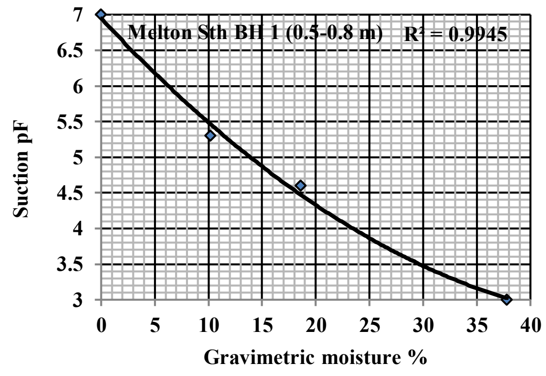


Silty Clay. Colour: Red-brown.
Δu_s = 3.2–4.0pF, I_{ccs} = 5.9%. 4.0–4.7pF, I_{ccs} = 3.7%.

Conditioned moisture C_W = 37.5%.
Conditioned suction Cs = 3.4pF.

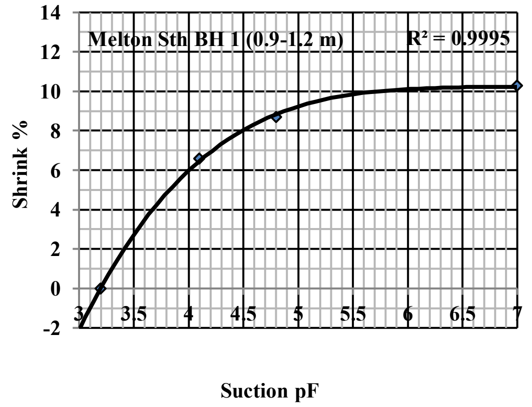
MELTON SOUTH– Suction V Shrink	MELTON SOUTH – SWCC

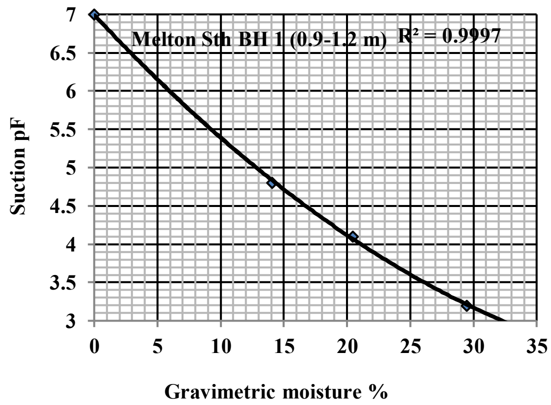




Silty Clay. Moist colour: Grey-red-brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 5.9%, 4.0–4.6pF, I_{ccs} = 3.0%

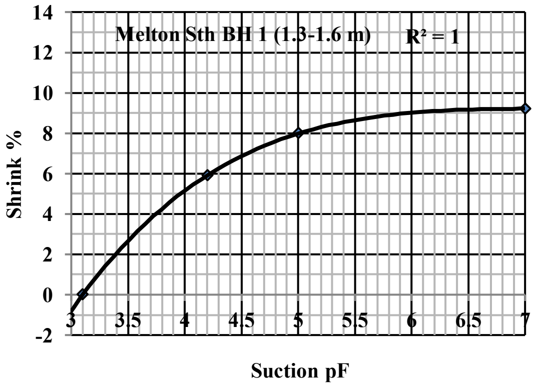
Conditioned moisture C_W = 38%.
Conditioned suction Cs = 3.0pF.

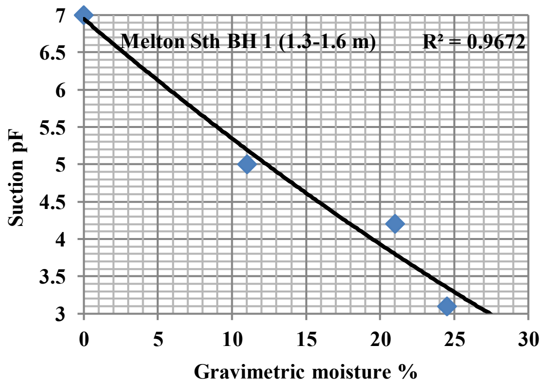




Silty Clay, Colour: Red-brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 7.8%, 4.0–4.6pF, I_{ccs} = 4.0%

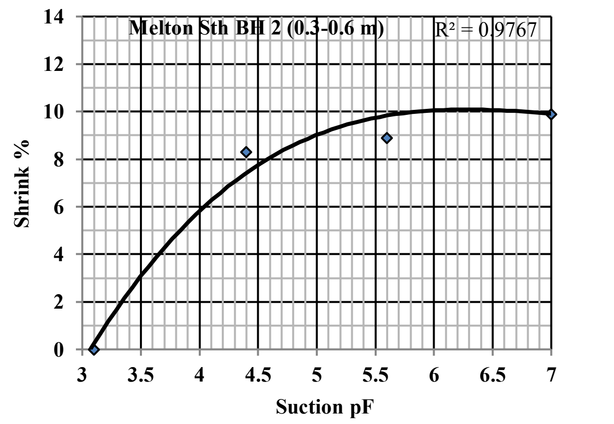
Conditioned moisture C_W = 29.5%.
Conditioned suction Cs = 3.2pF.



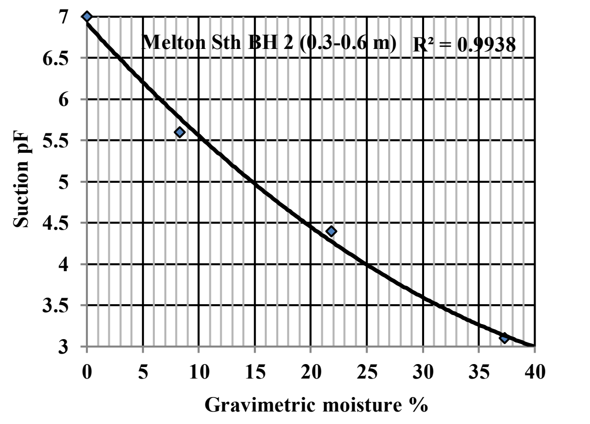


Sandy Silty Clay. Colour: Grey-red-brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 5.8%. 4.0–4.6pF, I_{ccs} = 3.2%.

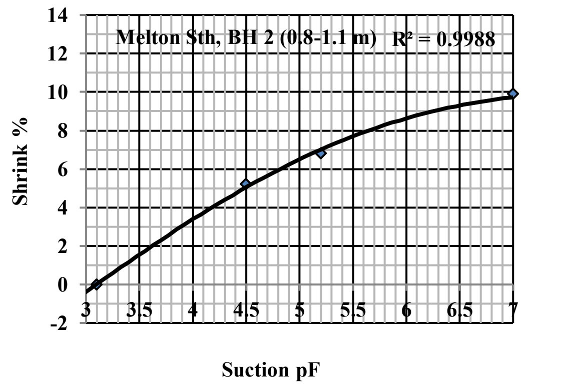
Conditioned moisture C_W = 24.5%.
Conditioned suction Cs = 3.1pF.



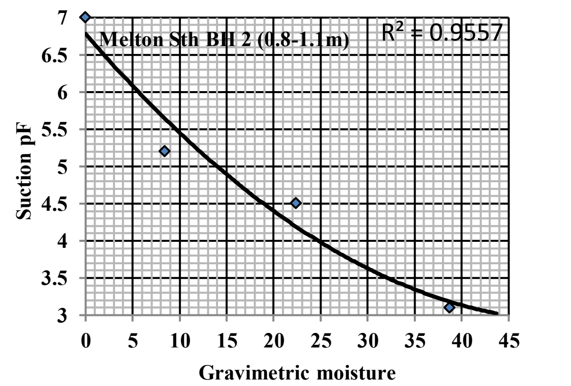
Sandy Silty Clay. Colour: Grey-red-brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 6.0%, 4.0–4.6pF, I_{ccs} = 3.7%



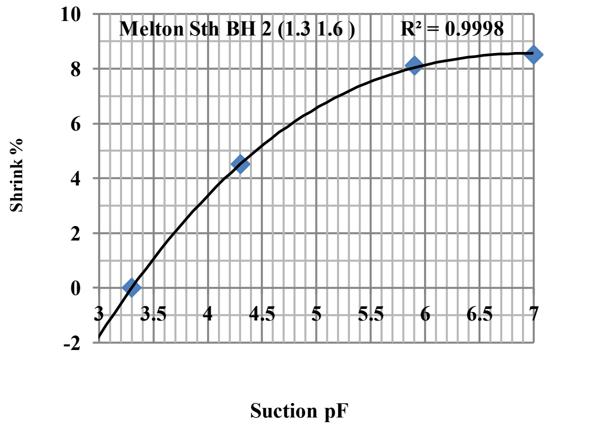
Conditioned moisture Cw = 37.5%.
Conditioned suction Cs = 3.1pF.



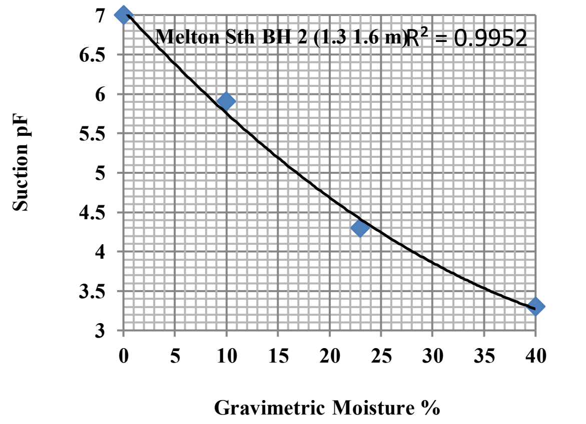
Silty Clay + Calcrete. Colour: Mottled grey/brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 3.8%, 4.0–4.6pF, I_{ccs} = 3.1%.



Conditioned moisture Cw = 39%.
Conditioned suction Cs = 3.1pF.



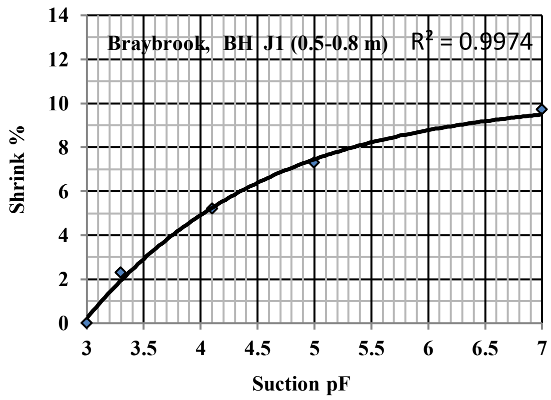
Silty Clay. Colour: Mottled Grey/brown.
Δu_s=3.1–4.0pF, I_{ccs} = 5.1%, 4.0–4.6pF, I_{ccs}=3.5%

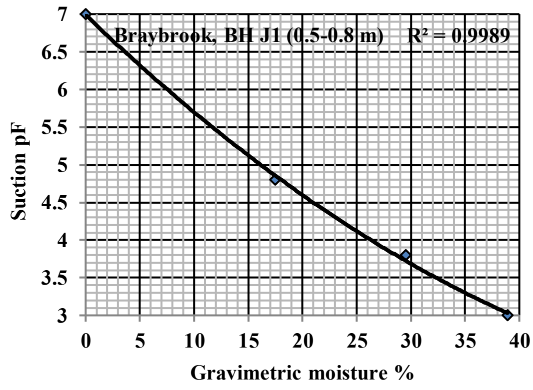


Conditioned moisture Cw = 40%.
Conditioned suction Cs = 3.3pF.

BRAYBROOK– Suction V Shrink

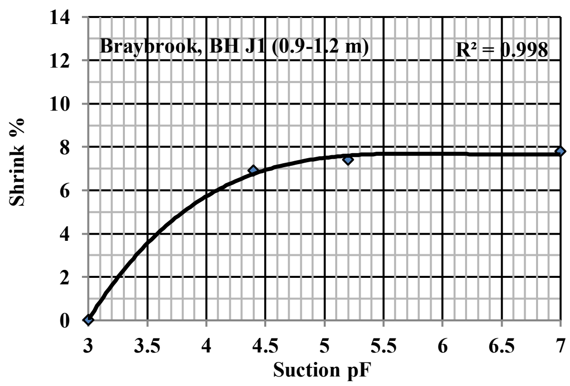
BRAYBROOK– SWCC

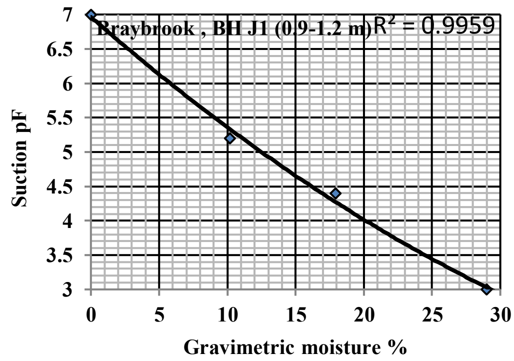




Silty Clay + Sand. Colour: Grey-brown.
Δu_s = 3.1–4.0pF, I_{ccs}= 4.6%, 4.0–4.6pF, I_{ccs}=2.8%

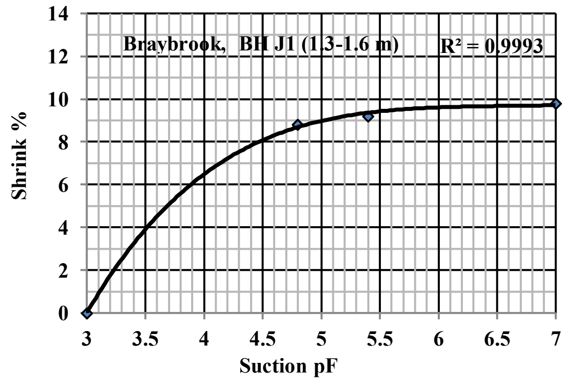
Conditioned moisture Cw = 39%.
Conditioned suction Cs = 3.0pF.

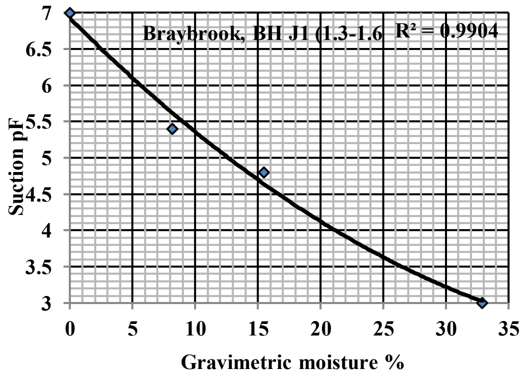




Silty Clay + sand. Colour: Grey-brown.
Δu_s = 3.1–4.0pF, I_{ccs}= 5.4%, 4.0–4.6pF, I_{ccs}= 2.3%

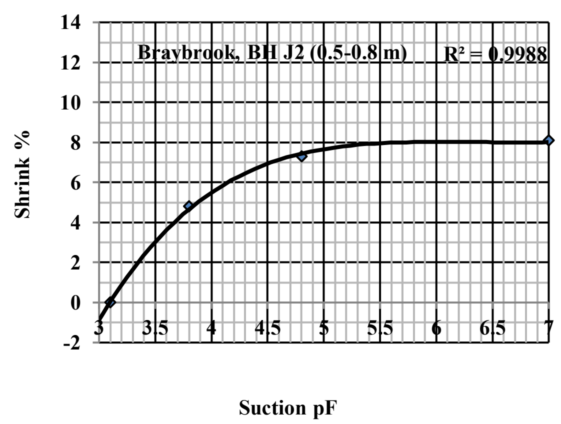
Conditioned moisture Cw = 29%.
Conditioned suction Cs = 3.0pF.

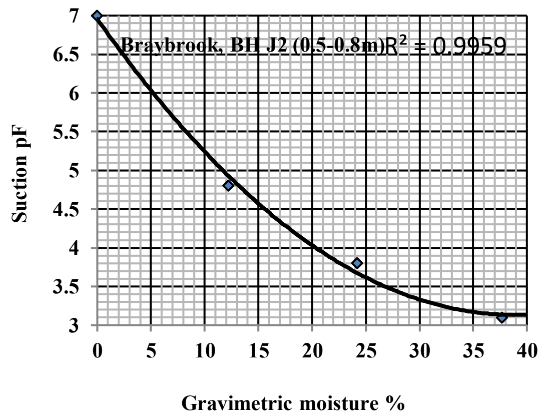




Silty Clay + sand. Colour: Grey-brown.
Δu_s = 3.1–4.0pF, I_{ccs}= 6.1%, 4.0–4.6pF, I_{ccs}= 3.2%.

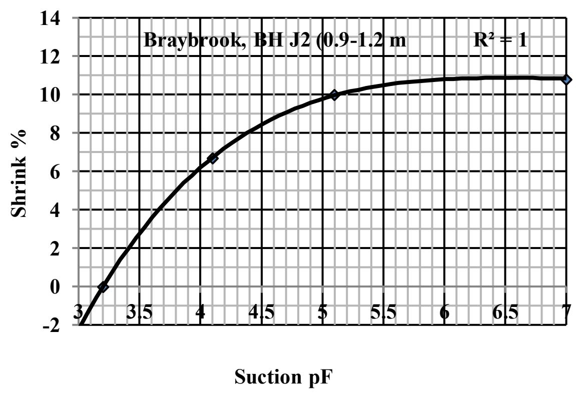
Conditioned moisture Cw= 33%.
Conditioned suction Cs = 3.0pF.

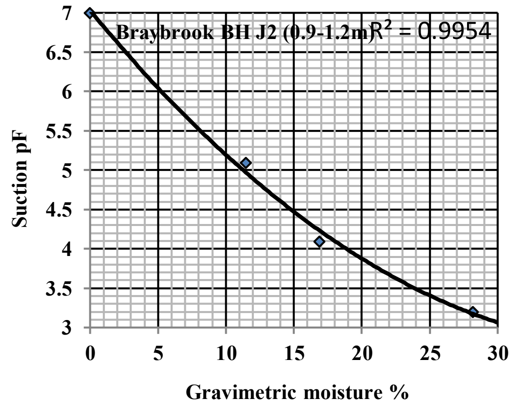




Silty Sandy Clay. Moist colour: Grey-brown.
Δu_s= 3.1–4.0pF, I_{ccs} = 6.1%, 4.0–4.6pF, I_{ccs}= 2.7%

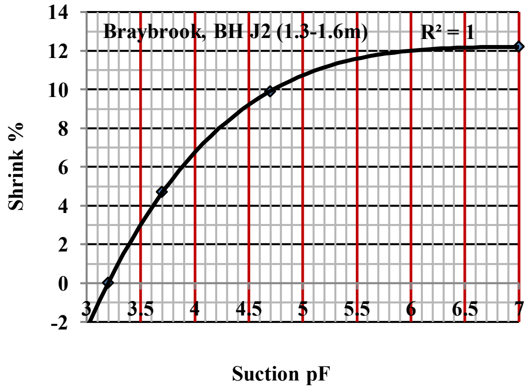
Conditioned moisture Cw = 38.0%.
Conditioned suction Cs = 3.1pF.

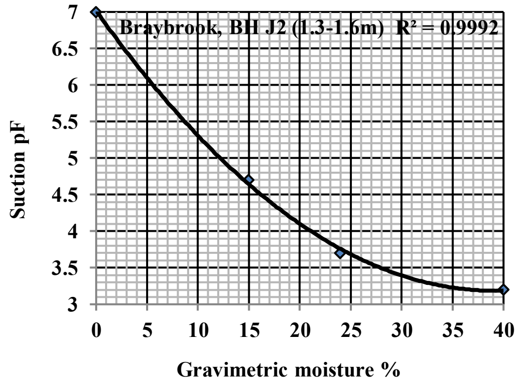




Silty Clay. Moist colour - Grey-brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 7.9%, 4.0–4.6pF, I_{ccs} = 4.3%.

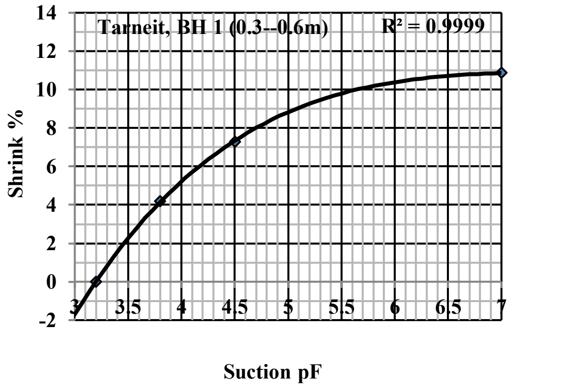
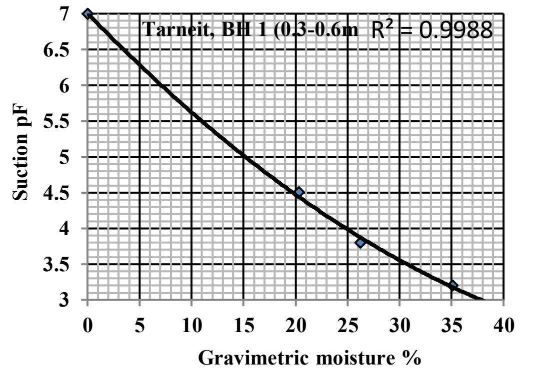
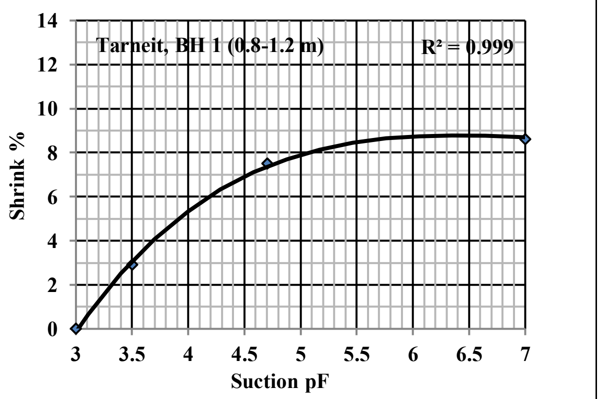
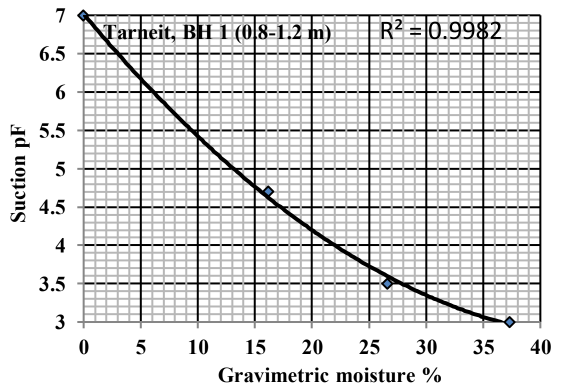
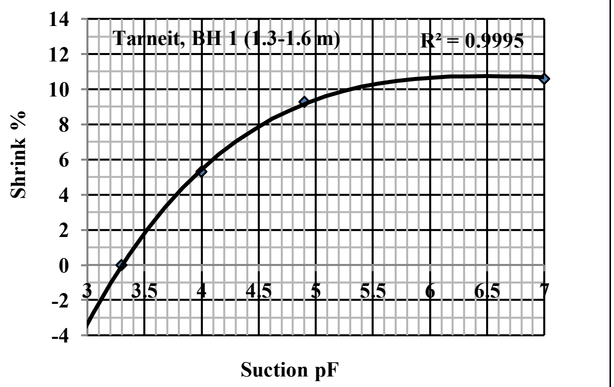
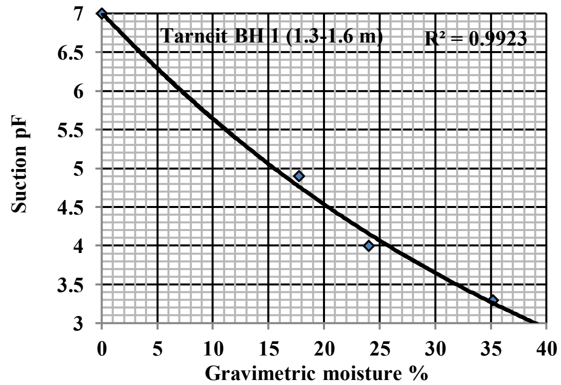
Conditioned moisture Cw = 28.5%.
Conditioned suction Cs = 3.2pF.

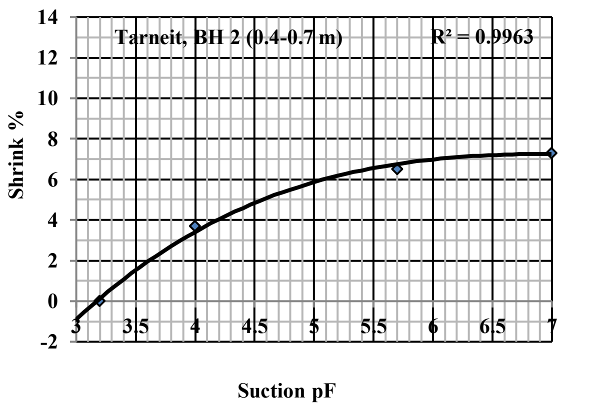


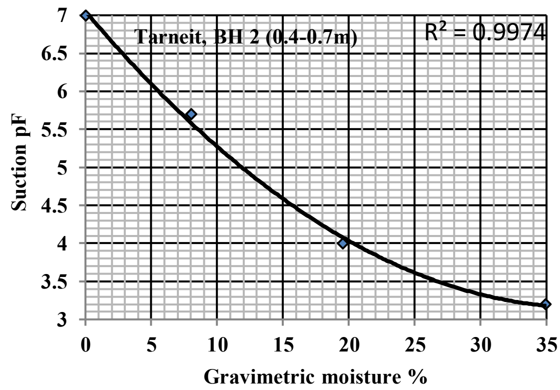


Silty Clay. Moist colour: Light brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 8.4%, 4.0–4.6pF, I_{ccs} = 5.0%

Conditioned moisture = 40%.
Conditioned suction = 3.2pF.

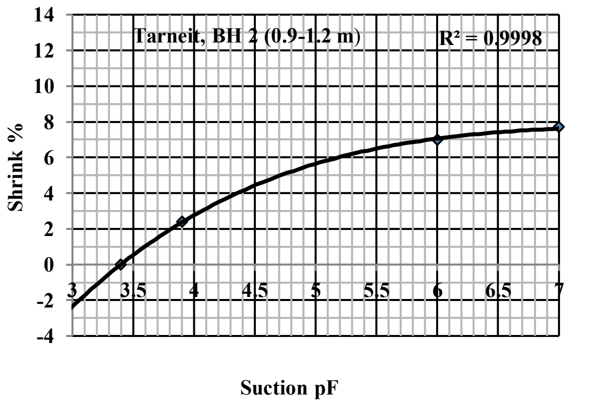
TARNEIT – Suction V Shrink	TARNEIT - SWCC
	
Silty Clay. Colour: Grey brown. **Δu_s = 3.1–4.0pF, I_{ccs} = 6.7%. 4.0–4.6pF, I_{ccs} = 4.2%.**	**Conditioned moisture C_W = 35%.** **Conditioned suction Cs = 3.2pF.**
	
Silty Clay, Colour: Light grey brown **Δu_s = 3.1–4.0pF, I_{ccs} = 5.4%. 4.0–4.6pF, I_{ccs} = 2.8%**	**Conditioned moisture C_W = 37.5%.** **Conditioned suction Cs = 3.0pF.**
	
Silty Clay. Colour: Grey brown. **Δu_s = 3.1–4.0pF, I_{ccs} = 8.2%. 4.0-4.6pF, I_{ccs} = 4.7%.**	**Conditioned moisture C_W = 35.5%.** **Conditioned suction Cs = 3.3pF.**

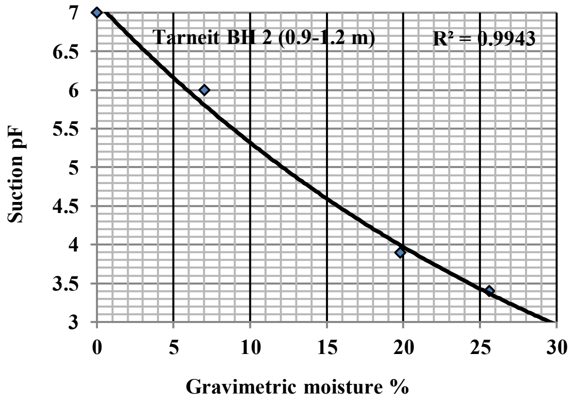




Silty Clay + calcrete. Colour: Light grey brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 4.2%. 4.0-4.6pF, I_{ccs} = 2.8%.

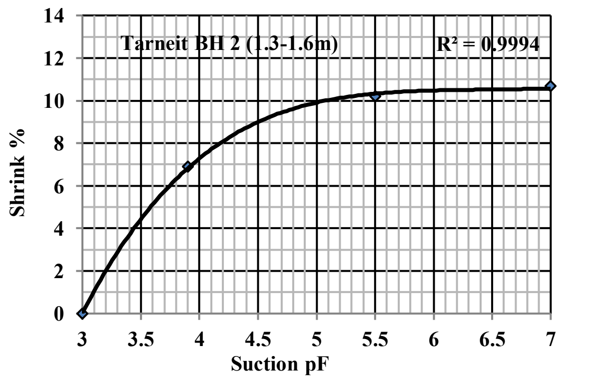
Conditioned moisture Cw = 35%.
Conditioned suction Cs = 3.2pF.

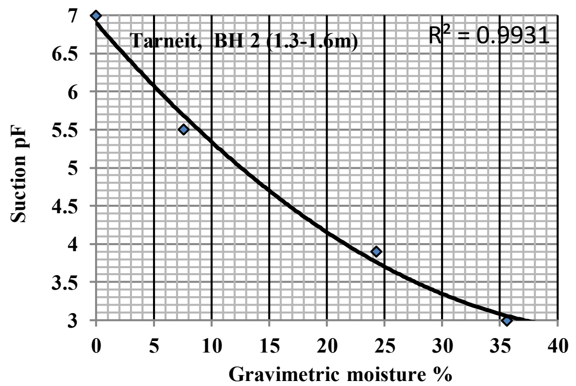




Silty Clay + minor calcrete.
Colour: Light grey brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 5.1%. 4.0-4.6pF, I_{ccs} = 3.2%

Conditioned moisture Cw = 26%.
Conditioned suction Cs = 3.4pF.





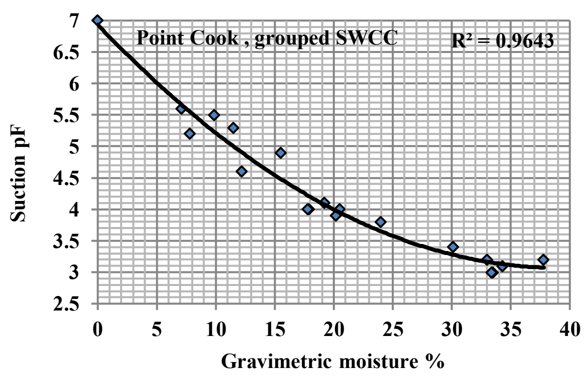
Silty Clay. Colour: Brown.
Δu_s = 3.1–4.0pF, I_{ccs} = 7.0%, 4.0-4.6pF. I_{ccs} = 3.3%

Conditioned moisture Cw = 36%.
Conditioned suction Cs = 3.0pF.

APPENDIX 6

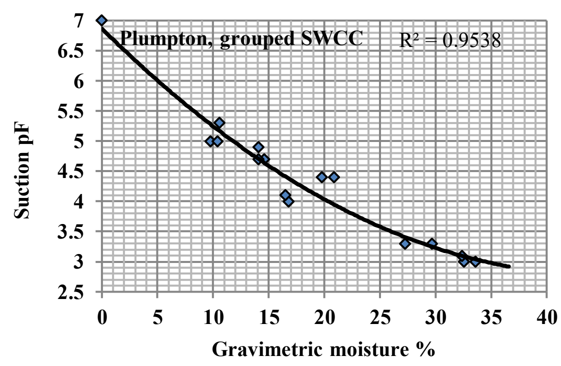
SWCC GRAPHS GROUPED BY LOCATION

POINT COOK



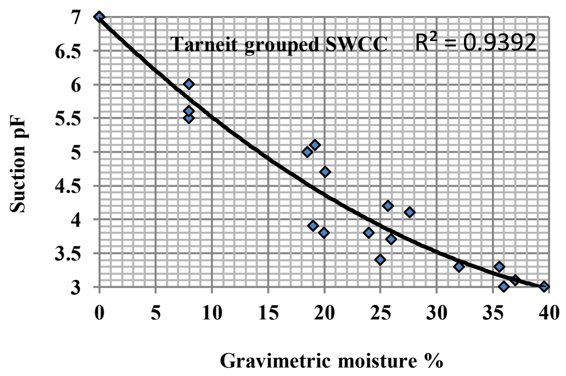
Δu_s = 3.1 – 4.6pF = 35% - 14%, Δw_s = 21%

PLUMPTON



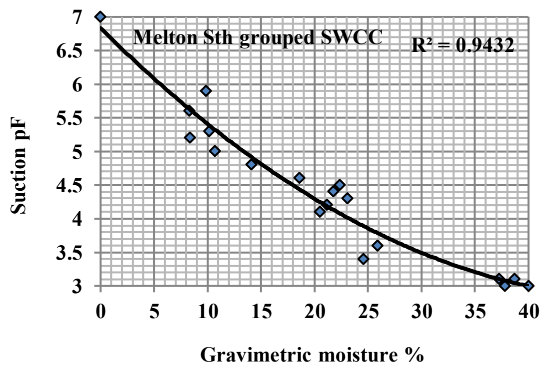
Δu_s = 3.1 – 4.6pF = 33% - 15%, Δw_s = 18%

TARNEIT



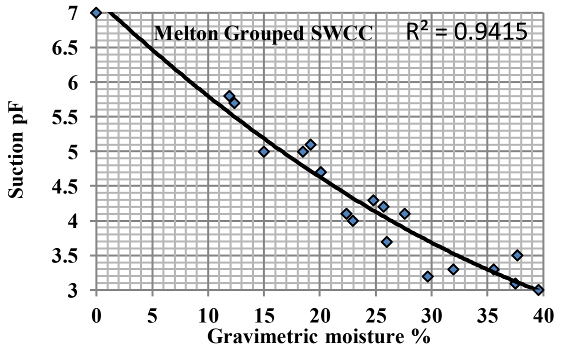
Δu_s = 3.1 – 4.6pF = 37% - 17.5%, Δw_s = 19.5%

MELTON SOUTH



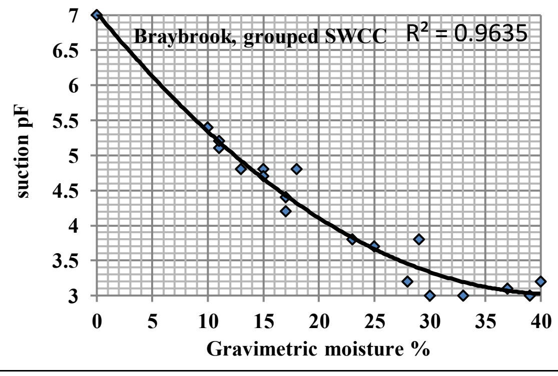
Δu_s = 3.1 – 4.6pF = 37% - 17%, Δw_s = 20%

MELTON



Δu_s = 3.1 – 4.6pF = 38% - 20%, Δw_s = 18%

BRAYBROOK



Δu_s = 3.1 – 4.6pF = 35% - 15.5%, Δw_s = 19.5%

Average Δw_s at Δu_s 3.1 – 4.6pF = 19.3%