SHORT AND CUMULATIVE LONG TERM IMPACTS OF SUBTERRANEAN CUT-OFF WALLS AND EXCAVATION DEWATERING ON ADJACENT STRUCTURES IN URBANISED AREAS

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ABSTRACT

This paper describes the hydrogeological and geotechnical assessment in relation to the short and cumulative long-term impacts associated with excavation, subterranean construction and dewatering in the Double Bay commercial area on the structural integrity of adjacent residential and commercial buildings. The paper comprises three main components, namely, (i) definition of groundwater study area and its geological and groundwater settings; (ii) assessment of potential cumulative impact of future developments on long-term groundwater change; and (iii) assessment of potential impact of short-term construction dewatering on risks of damage of adjacent buildings.

1 INTRODUCTION

Urban development is increasingly aiming to maximise the value of land in the Double Bay region. Double Bay is a harbour side eastern suburb of Sydney, in the state of New South Wales. Many developments are considering the construction of basements, underground car parking and other associated below ground structures. Where the water table is intersected, temporary dewatering is required to ensure safe and stable construction conditions. Partial or full depth penetration cut-off walls are sometimes adopted for the purpose of dewatering the sites. The potential for these cut-off walls to cause disruption to the groundwater flow, either by allowing the flow of water beneath the wall during dewatering within the sites or by altering the long-term groundwater seepage patterns requires careful consideration. The magnitude of these groundwater level impacts can be significant when the developments are considered from a cumulative perspective. In terms of the built environment, the depressurisation of compressible sediments can lead to differential settlement, which have significant impacts on existing buildings. This paper outlines the geotechnical and hydrogeological assessment in relation to: (i) the impact of long term regional groundwater level change due to future developments and (ii) the impact of surface settlement as a result of groundwater drawdown caused by short term construction dewatering.

2 REGIONAL SETTING

Double Bay sits in the valley between the ridgelines of Edgecliff/Darling Point and Bellevue Hill/Point Piper, occupying the low elevation harbour front area. The valley follows the former Cooper Creek alignment, which emanates from Cooper Park, running from Bellevue Hill, north to the harbour (Figure 1). This watercourse, and its entry into the harbour, has resulted in variably deep alluvial sediments within the valley base, with the greatest depth of soils close to the bay, where boreholes have encountered greater than 40 m of mainly coarse grained sediments, occasionally peaty sands with stiff clay basal layers. Climate data from the Bureau of Meteorology indicates an average annual rainfall of around 1230 mm.

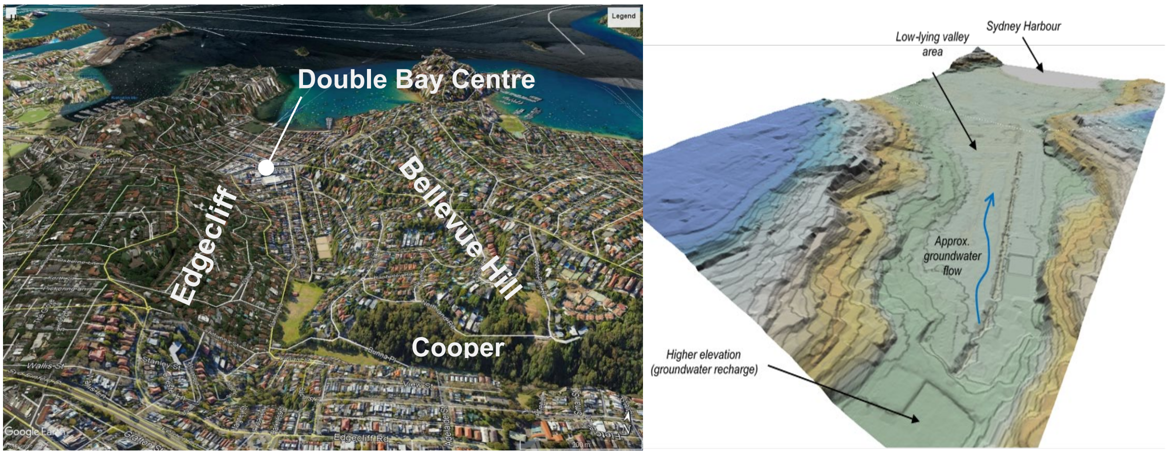


Figure 1: Double Bay regional setting

3 GEOLOGICAL SETTING

Over two hundred available boreholes in the Double Bay area dating back to the 70's have been compiled to create a 3D geological model using the commercially available software package Leapfrog. Figure 3 shows the spatial distribution of the available geotechnical data points. Figure 2 shows the 3D visualisation of the ground conditions. It can be seen that Double Bay was originally a sandstone valley that has now been buried with sand dominated alluvium.

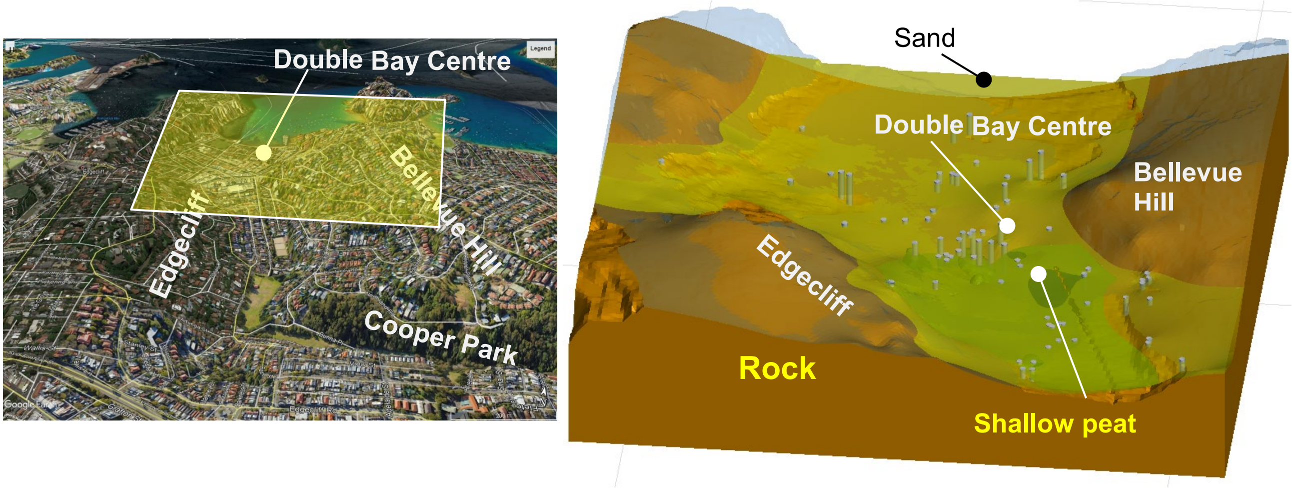
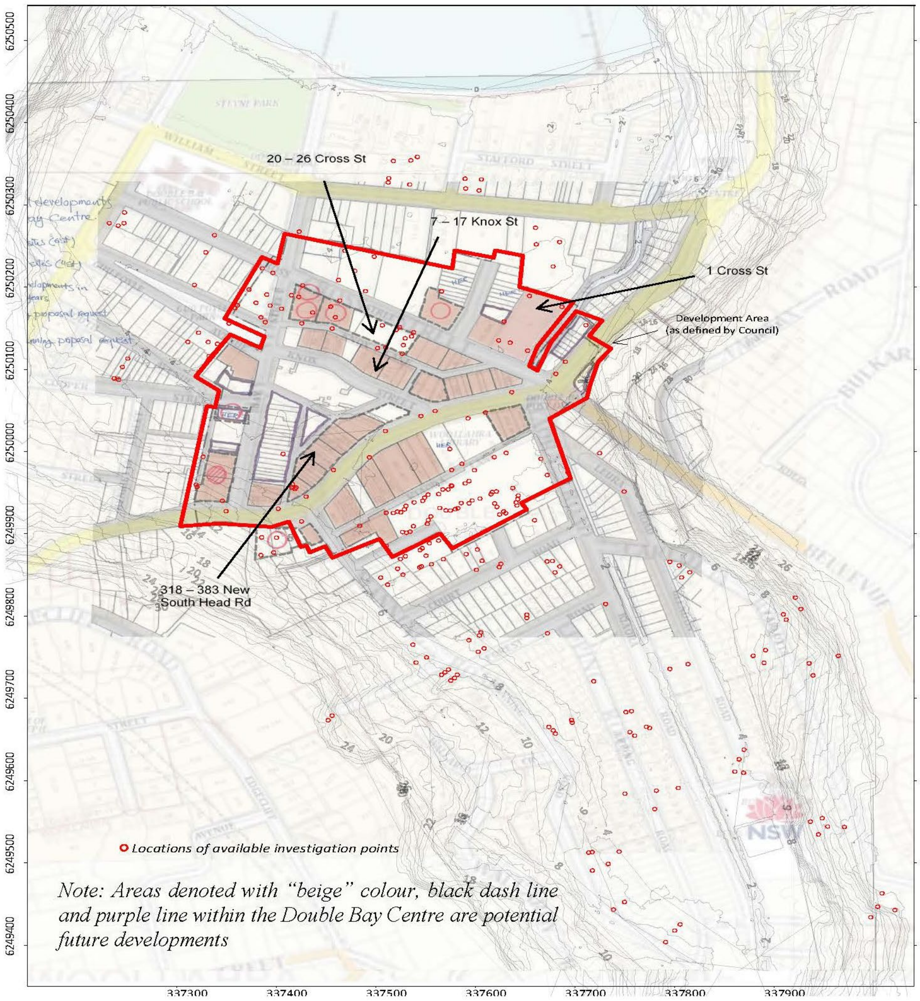


Figure 2: 3D geological model generated using Leapfrog software program



Note: Areas denoted with "beige" colour, black dash line and purple line within the Double Bay Centre are potential future developments

Figure 3: Locations of all available geotechnical investigations in Double Bay

The subsurface profile encountered in the Double Bay area and delineated in our geological model can be broadly categorised into three main strata as follows:

- *Bedrock* – Hawkesbury Sandstone underlies the Quaternary deposits. Hawkesbury Sandstone generally comprises medium to coarse grained quartz sandstone with minor shale and laminate lenses. It is typically extremely to highly weathered and fractured at the top and becomes moderately to slightly weathered and only slightly fractured with depth. Collation of available data suggests that the weathered sandstone bedrock surface follows the general shape of ground surface. An assessed contour of bedrock level is presented in Figure 4a.
- *Alluvium* – The alluvial region generally follows the shape of the valley. The yellow highlight shown in Figure 4a outlines the approximate extent of the alluvium over the sandstone bedrock. A geological section drawn along section A-A was developed in the north-south direction roughly parallel to the direction of groundwater flow. This geological section, shown in Figure 5, indicates that the sand dominated alluvium generally fill the incised valley and extend to a maximum depth of about 35 m as the bed rock dips north towards Sydney Harbour. The alluvial sand overlying the bedrock is generally clean and medium to fine grained. It varies in consistency from loose at shallow depth to very dense at depth. Interlayered sandy clays, clays and lower peats of typically stiff to very stiff consistency are also encountered. It appears that these bands are found at lower depths and encountered mainly at the southern Double Bay study area to the south of Kiaora Lane.
- *Upper Peat* – The upper peat layers were considered to be the most compressible deposits and are generally encountered at shallow depth of 0.5 – 2.5 m. Previous investigations indicated that the dark grey peat lenses are of high plasticity with high moisture content organic clay materials. The presence of peat has been observed intermittently although it was consistently noted in the area located to the south of Forest Rd (see Figures 4a and 4b). The upper peat layer have thin thicknesses of generally less than 1.5 m, but they are considered to have significant influence on dewatering induced settlements and further discussion of this material is given in Section 6.

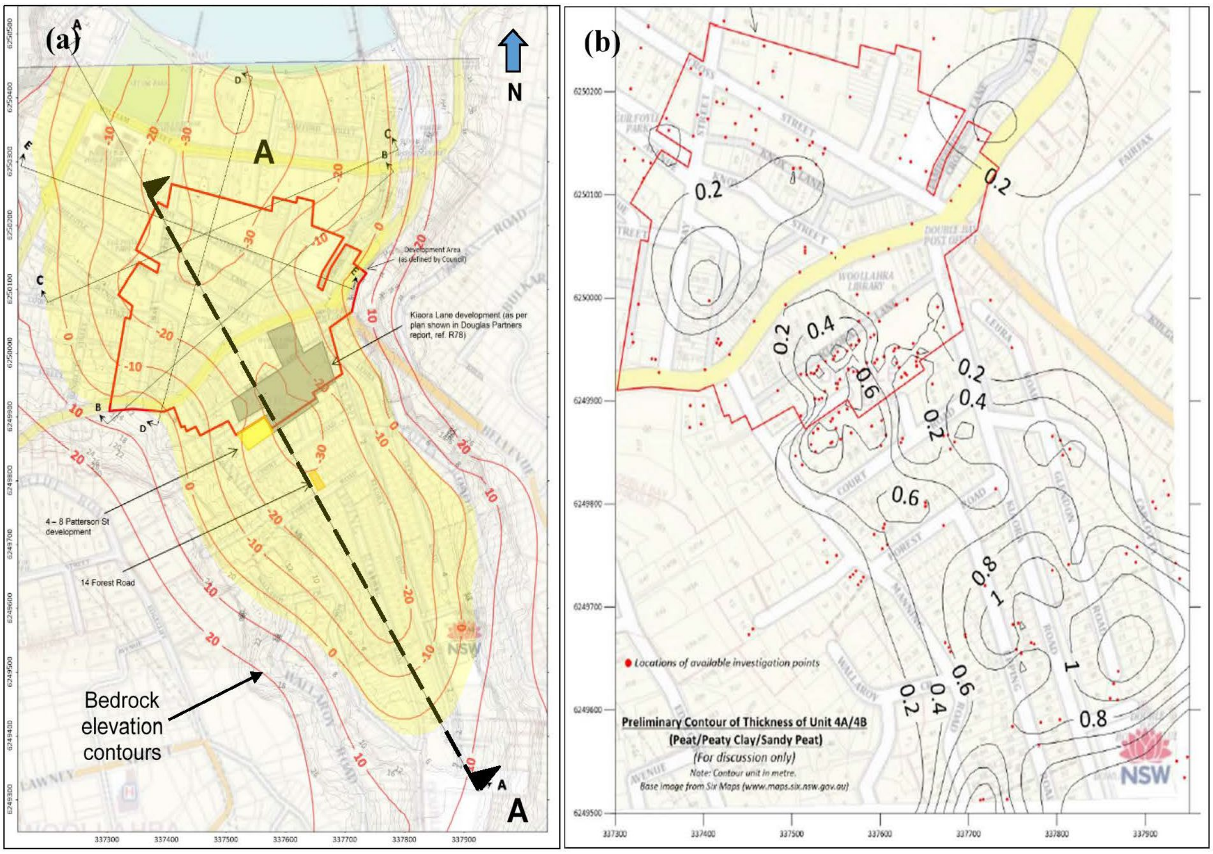


Figure 4: (a) Contour of top elevation of bedrock; (b) Contour of upper peat thickness

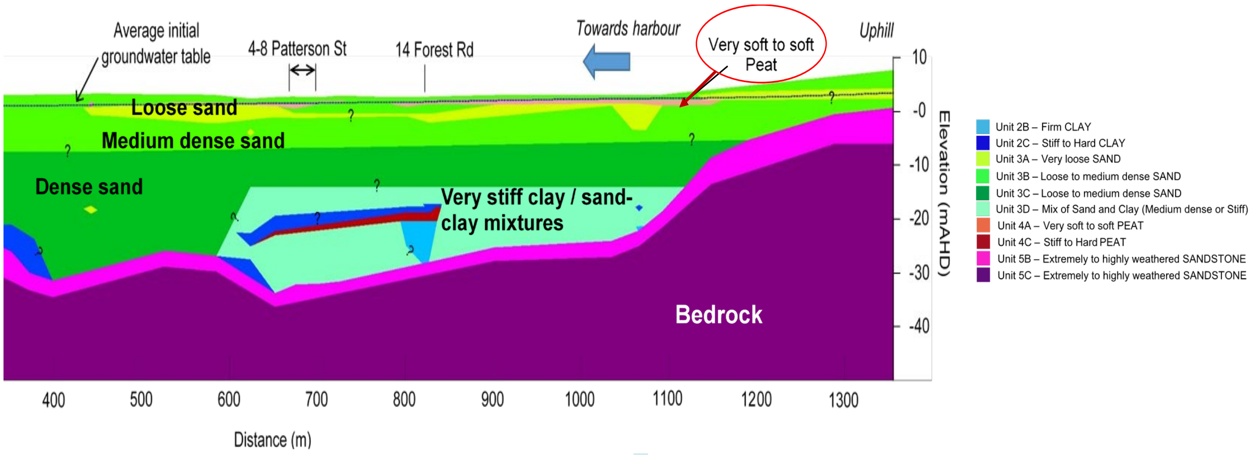


Figure 5: Geotechnical profile along Section A-A in Figure 4a

4 GROUNDWATER SETTING

4.1 OVERVIEW

Hydro-stratigraphic units (HSUs) are zones within the groundwater system that have similar hydrogeological properties and behave in a similar manner from the point of view of groundwater flow. For the Double Bay area, the hydro-stratigraphy is broadly divided into the Alluvium, comprising unconsolidated sediments, and the Bedrock, which underlies the Alluvium and forms a fractured rock aquifer. The Alluvium forms an unconfined aquifer, within which the water table (upper surface of the shallow groundwater system) is located. The Bedrock is confined beneath the Alluvium within the Double Bay area, and becomes unconfined where it outcrops outside of the valley and forms a regional aquifer.

Groundwater use within the study area is based on the data extracted from the Bureau of Meteorology(BoM)'s Australian Groundwater Explorer, which identified 40 bores in the approximate Double Bay area. The uses of these bores were identified as following (although the operational status of these groundwater bores is not known): (i) 28 bores for water supply; (ii) 6 bores for monitoring; (iii) 1 bore for irrigation; (iv) 1 bore for dewatering; and (v) 4 other bores with unknown purposes. The depths of these bores range from 2.75 m to 52 m, with an average depth of 9.6 m.

A search of Water-NSW also identified 48 bores in the approximate Double Bay area, however, this dataset did not identify the use of each bore. The data obtained from the review of existing geotechnical and hydrogeological investigation reports indicate several bores constructed within the Double Bay area specifically for monitoring purposes. The data available from these investigation reports as well as those from the Water-NSW database and BoM database provide the basis for interpreting the groundwater flow directions and trends in the following section.

4.2 GROUNDWATER FLOW DIRECTION

To assess groundwater flow directions in the Double Bay area, contours of water table have been prepared using groundwater level data extracted from the existing geotechnical and hydrogeological investigation reports (Figure 6). The contours are interpreted from groundwater levels taken at different points in time, many of which are opportunistic measurements collected from open-holes at the time of field investigations. As such, there are some local variability and the contours should be considered indicative only. Despite these limitations, the interpreted contours provide useful indications of groundwater flow directions, confirming the northerly groundwater flow towards the coastal boundary along the centreline of the valley and flow from topographically elevated areas along the valley edges towards the valley centre. The hydraulic gradient is around 0.003 along the valley centreline, indicating a gentle hydraulic gradient across the Alluvium comprising permeable sediments. The data currently available is insufficient to ascertain local variability in the water table due to anthropogenic influences such as groundwater pumping and existing basement structures.

4.3 GROUNDWATER TREND

The available groundwater monitoring data within the Double Bay area show seasonal variations ranging from around 0.5 to 1 m over the long term with a clear correlation with rainfall. This indicates that the water table within the Alluvium is sensitive to rainfall-derived recharge (the Alluvium is readily replenished by recharge). The range of seasonal fluctuation is smaller at bores closer to the coastal boundary where the groundwater level is constrained at mean sea level. This can be seen in Figure 7, where BH6 is approximately 200 m from the coastal boundary and shows much smaller seasonal variations than BH1 located approximately 400 m farther inland.

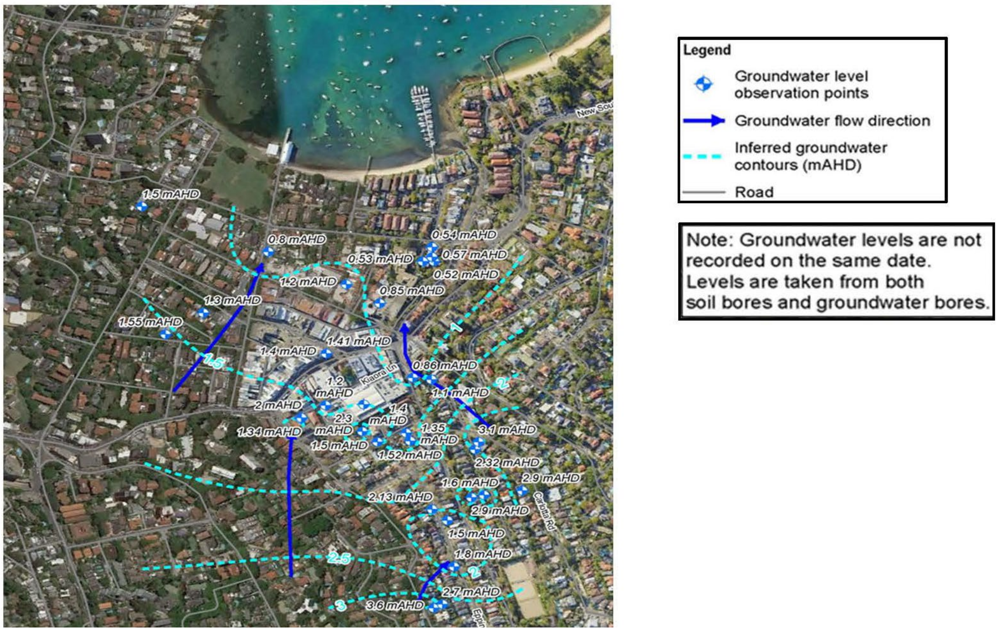


Figure 6: Interpreted groundwater contours and flow directions

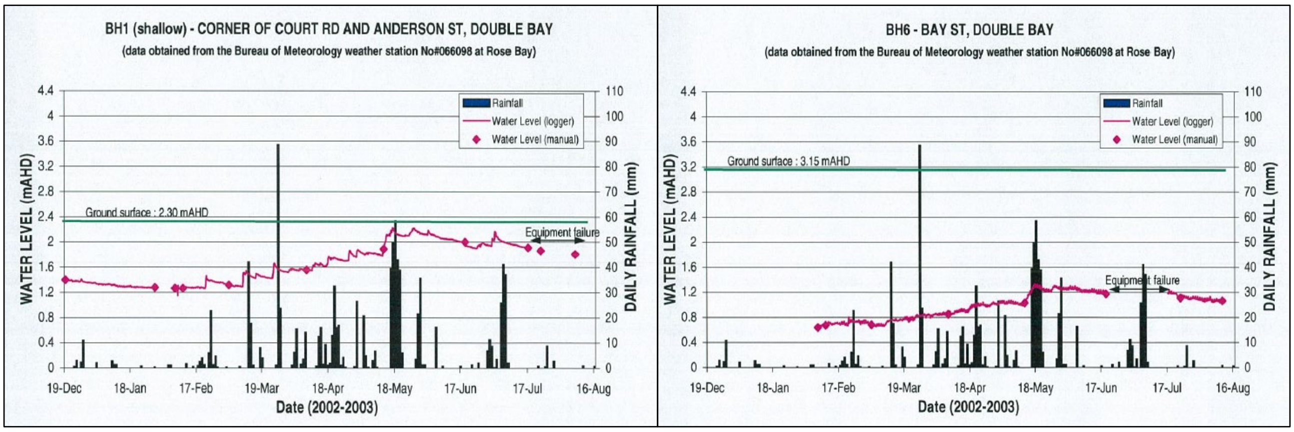


Figure 7: Seasonal trend (after Coffey, 2003)

4.4 HYDROGEOLOGICAL PARAMETERS

From the point of view of groundwater flow, the critical in-situ material properties are the hydraulic conductivity and storage coefficients (specific yield and specific storage). These properties control the resistance of the subsurface material to flow and the rate in which it is drained and/or re-saturated in response to stresses (and the rate in which aquifer pressure is propagated in a fully confined system at depth). Components of inflow and outflow, such as recharge and evapotranspiration, are also important although these are rarely measured in the field and more commonly inferred through other means (such as model calibration), using field-derived estimates of in-situ properties as constraints.

This section provides a summary of prior estimates of hydrogeological properties derived from field testing and modelling undertaken in the Double Bay area. These estimates provide the basis for parameterising and calibrating the regional numerical groundwater model described in Section 5.2.

Aquifer testing completed as part of geotechnical and hydrogeological investigations in the Double Bay area include CPTU dissipation testing and in-situ permeability testing (such as falling and rising head tests). Table 1 summarises the horizontal hydraulic conductivity values collected during field investigations. The majority of these tests have targeted discrete horizons within the Alluvium, as flow into shallow excavations are controlled by the properties of this shallow aquifer. While low hydraulic conductivity values have been derived from discrete clay lenses, the abundance of sand within the Alluvium and high hydraulic conductivities associated with the sand intervals indicate that the aquifer as a whole behaves as a high transmissivity system.

Limited information is available from the bedrock. The hydraulic conductivity of the weathered sandstone bedrock could be variable depending on the weathering profile and presence of jointing in the rock. Information available from other parts of the Sydney area indicate that the mean horizontal hydraulic conductivity in the upper 100 m of the Hawkesbury Sandstone ranges from around 0.01 to 0.1 m/day (around 10^{-5} to 10^{-4} cm/sec) (Tammetta and Hawkes, 2009). There are no estimates of vertical hydraulic conductivity although a horizontal to vertical permeability ratio of 10:1 has been reported (Longmac Associates, 1990), which is common in layered sedimentary aquifer systems.

There are no site specific estimates of storage coefficients. Specific yield of 0.1 to 0.3 is commonly assumed for the alluvium comprising fine sands and specific storage of 10^{-6} to 10^{-4} /m is reported in the literature for confined Hawkesbury Sandstone (GHD, 2015). For most lithologies, specific storage of 10^{-6} to 10^{-5} /m is considered realistic, with recent work by Rau *et al.* (2018) suggesting a plausible upper threshold of around 1.3×10^{-5} /m for specific storage in confined aquifers.

Table 1: Aquifer test data

Lithology	Method	Reference	Number of tests	Hori. permeability (cm/sec)
Sand with silt	In-situ permeability	Longmac Associates (1998)	3	$4.9\text{x}10^{-4}$ to $2.3\text{x}10^{-3}$
Sand with silt	In-situ permeability	Coffey (2003)	1	$<1\text{x}10^{-3}$
Sand	In-situ permeability	Longmac Associates (1990)	-	$6\text{x}10^{-4}$ to $2\ \text{x}10^{-2}$
Sand	In-situ permeability	Coffey (2003)	7	$1\text{x}10^{-3}$ to $1\text{x}10^{-2}$
Sand	In-situ permeability	Douglas Partners (2016)	1	$1.2\text{x}10^{-2}$ to $2.3\text{x}10^{-2}$
Clay	CPTU	Longmac Associates (1998)	10	$2.5\text{x}10^{-5}$ to $2\text{x}10^{-4}$
Clay bands	Laboratory testing	Coffey (1989)	2	$7.1\text{x}10^{-9}$ to $5.8\text{x}10^{-8}$
Clay/peat	In-situ permeability	Longmac Associates (1990)	–	$1\text{x}10^{-7}$ to $6\text{x}10^{-4}$
Sandstone	In-situ permeability	Longmac Associates (1998)	1	$9.4\text{x}10^{-6}$
Sandstone	In-situ permeability	Longmac Associates (1990)	–	Negligible small to $9\text{x}10^{-4}$

5 REGIONAL GROUNDWATER MODELLING

5.1 OVERVIEW

Due to the shallow water table in the Double Bay area, there is high potential for future developments to interact with groundwater. Regional groundwater modelling was carried out to provide:

- Spatial distribution of piezometric heads, depth to groundwater and associated seasonal range across the study area, such that the likely level of groundwater interference at future development sites could be understood.
- Potential cumulative long-term impacts of multiple subterranean structures (basements), including the magnitude and spatial extent of changes to the water table.

The regional groundwater modelling was carried out using the commercially available software program MODFLOW-USG (Panday *et al.*, 2013). The model domain covers the local groundwater catchment. The domain is large enough to fully enclose the extent of the Alluvium and capture the influence of key hydrological stresses. Along the coastal boundary, a constant head boundary condition is assigned with a head value of 0.1 mAHD. Elsewhere, a no-flow boundary condition is assumed along the model boundary that follows inferred regional flow divides (topographic ridge). Recharge and evapotranspiration are prescribed to the uppermost nodes near ground surface. Two recharge zones have been defined for the Alluvium and the outcropping Bedrock, to account for different recharge rates expected in these units of different properties. Both recharge and evapotranspiration rates have been adjusted during model calibration and are described further in Section 5.2.

The model layers are based on the Leapfrog geological model and includes the Alluvium, Peat and Bedrock. Although the Peat lenses are generally thin or localised, they have been incorporated into the model for consistency with the geological modelling. Figure 8 presents a cross-section that outlines the model layers. With the exception of the Bedrock layer (layer 7), each model layer is discontinuous and pinched out against the adjacent unit. This means there are areas where some model layers are absent e.g. layer 1 locally overlies layer 4 directly.

5.2 MODEL CALIBRATION

The regional groundwater model was calibrated transiently by comparing the simulated water levels against a combination of single groundwater level measurements collected from 25 bores at different times and time series of groundwater level measurements obtained from 8 monitoring bores. The model calibration period starts in January 2002 and finishes at the end of 2019, capturing 18-years of climate data. The model parameters have been adjusted during calibration to derive representative hydraulic conductivity (horizontal and vertical), specific yield and specific storage for each HSU. Recharge is calculated as a percentage of average daily rainfall for each stress period. Rainfall is first converted to recharge using a factor and applied over the Alluvium. This Alluvium recharge is then converted to Bedrock recharge using another factor. This two-stage approach maintains a sensible ratio between the two recharge rates throughout the calibration process, ensuring that recharge applied over less permeable Bedrock is no greater than recharge over more permeable Alluvium. Evapotranspiration rate and extinction depth are adjusted as single model-wide values.

Table 2 summarises the calibrated model parameters. These parameter values are generally consistent with the published range of values. Figure 9 presents examples of calibration results for the available data of several monitoring bores within the study area. The hydrographs show that the modelled heads match the observed heads reasonably well, with seasonal fluctuations appropriately replicated. In particular, smaller seasonal fluctuations observed closer to the coastal boundary are also simulated by the model consistent with the expected groundwater behaviour.

5.3 ASSESSED DEPTH TO GROUNDWATER TABLE

Figure 10 presents maps of depth to groundwater for the wet and dry periods. These maps have been generated by subtracting the modelled surface of the water table from the regional ground model. The maps provide indications of areas where the water table is shallow and the expected seasonal range. For example, Figure 10b indicates areas of shallow water table (< 1m below ground) in the area to the south of Kioara Lane during wet period, consistent with high groundwater levels measured in a monitoring bore located in this area (refer to BH1 in Figure 7). Within the context of potential future developments, the maps provide useful indications of the risk of groundwater interference to be outlined in Section 5.4.

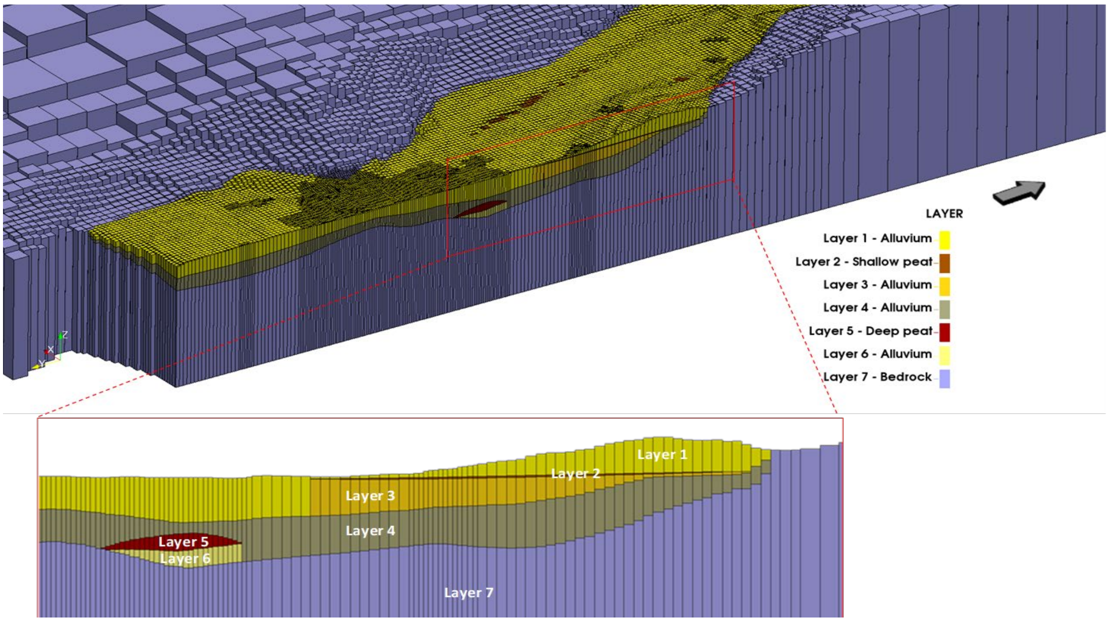


Figure 8: Regional groundwater model

Table 2: Calibrated model parameters

Parameter	Calibration values
Alluvium horizontal hydraulic conductivity (K_H)	0.5 to 10 m/d (average 3 m/d)
Alluvium hydraulic conductivity anisotropy (K_H/K_V)	10.47
Peat horizontal hydraulic conductivity (K_H)	0.035 m/d
Peat hydraulic conductivity anisotropy (K_H/K_V)	6.36
Bedrock horizontal hydraulic conductivity (K_H)	0.044 m/d
Bedrock hydraulic conductivity anisotropy (K_H/K_V)	11.05
Alluvium specific yield (Sy)	0.08
Alluvium specific storage (Ss)	1.2 x 10^{-5} /m
Peat specific yield (Sy)	0.085
Peat specific storage (Ss)	2.7 x 10^{-6} /m
Bedrock specific yield (Sy)	0.022
Bedrock specific storage (Ss)	5 x 10^{-6} /m
Alluvium recharge	20% rainfall (average 237 mm/yr)
Bedrock recharge	4.4% rainfall (average 52 mm/yr)
Evapotranspiration	1200 mm/yr
Evapotranspiration extinction depth	2.5 m

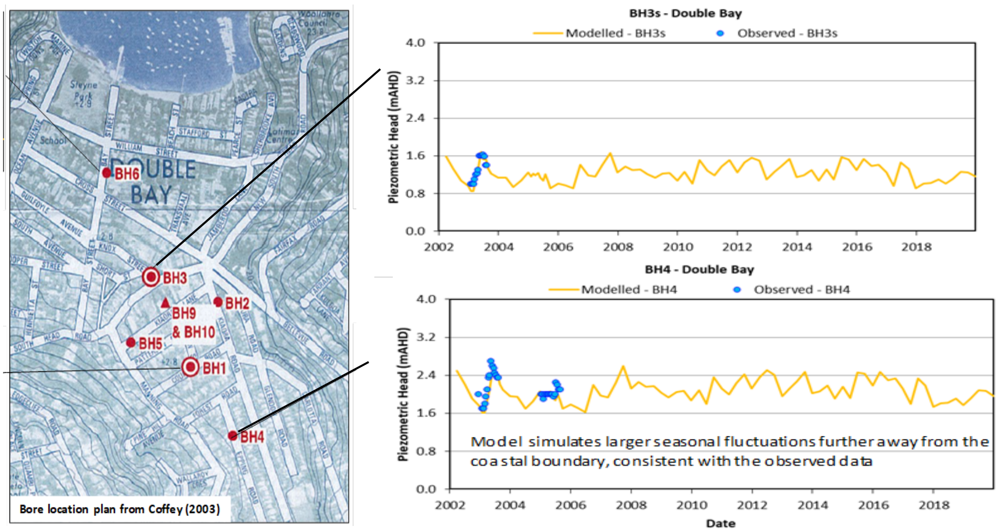


Figure 9: Modelled hydrographs (Courtesy of Coffee for the borehole location plan)

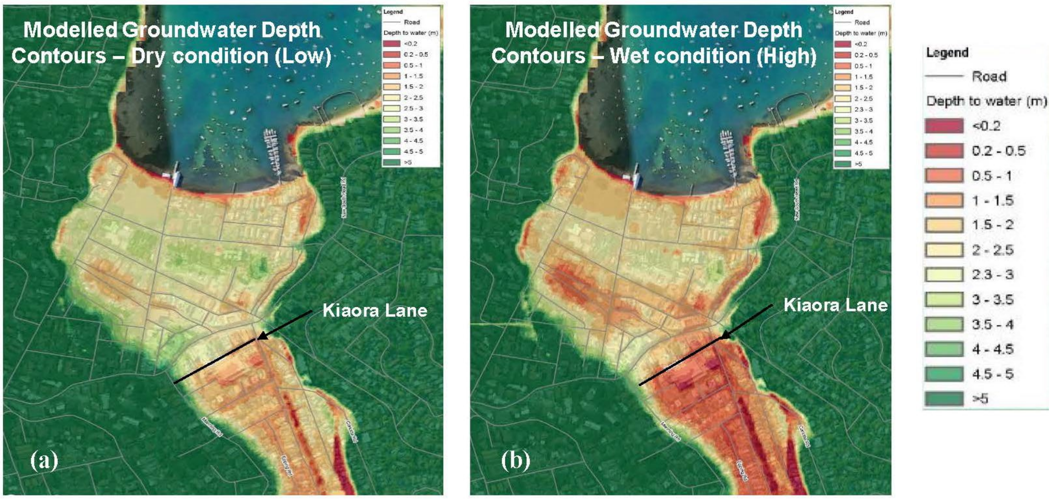


Figure 10: Modelled depth to groundwater for (a) dry season and (b) wet season

5.4 POTENTIAL LONG TERM CHANGES TO WATER TABLE WITH FUTURE DEVELOPMENTS

The potential long term cumulative impacts of future basements have been assessed by incorporating these features into the calibrated model as zones of low permeability material. The future developments being considered in the present assessment are indicated in Figure 3. Two scenarios with regards to these future developments have been modelled:

- A full cut-off scenario where the basements/low permeability zones are assumed to fully extend to the base of the Alluvium/ top of Bedrock.
- A partial cut-off scenario where the basements are assumed to terminate 12 m below ground surface, allowing groundwater to flow below them.

Figure 11 presents the modelled maximum change in the water table for the partial cut-off and full cut-off scenarios. The positive change indicates drawdown (lowering) of the water table and negative change indicates mounding (raising) of the water table. The figures indicate the following:

- The partial cut-off results in localised and minor lowering of water table (less than 200 mm) at the northern side of Double Bay Centre.
- The full cut-off results in mounding of the water table on the up gradient side and drawdown on the down gradient side due to impedance of groundwater flow. The maximum drawdown and mounding simulated by the model are generally less than 0.3 m. Up to around 0.4 m of mounding is simulated in the southwest, where groundwater flows from the valley edge; however, this occurs in an area of low risk of groundwater interference where the depth to groundwater is greater than 2 m.

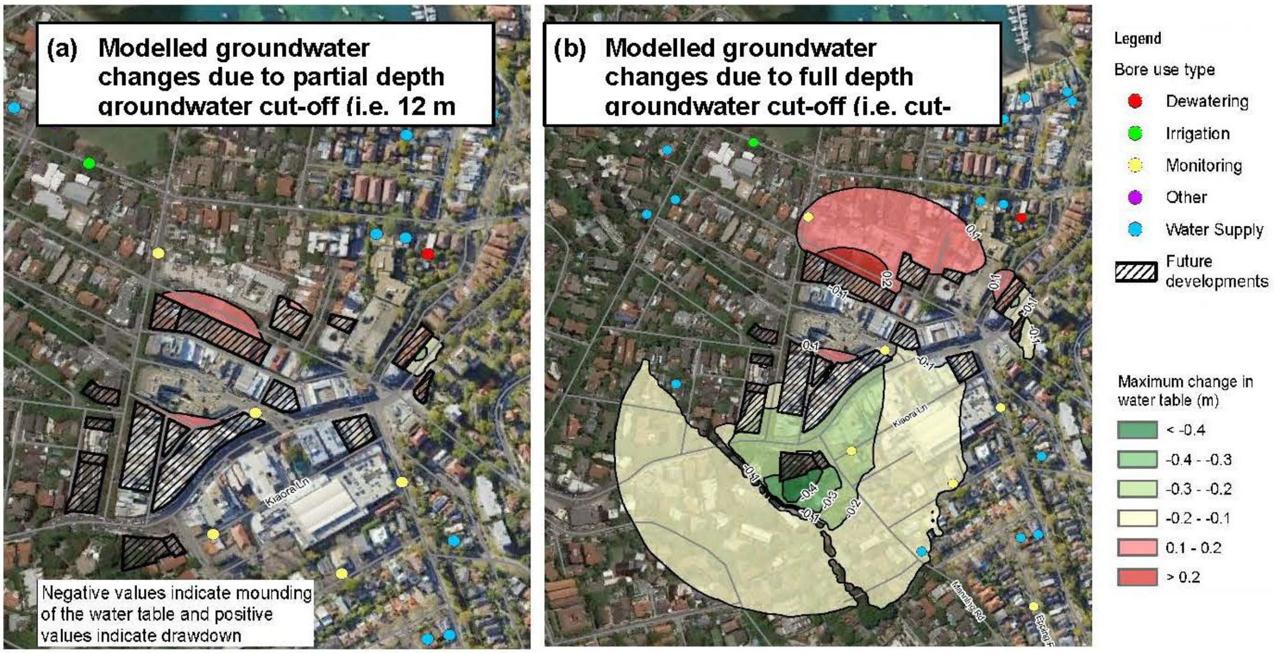


Figure 11: Contours of maximum change in long term water table for (a) partial cut-off and (b) full cut-off cases

6 GEOTECHNICAL ASSESSMENT OF DEWATERING INDUCED SETTLEMENT

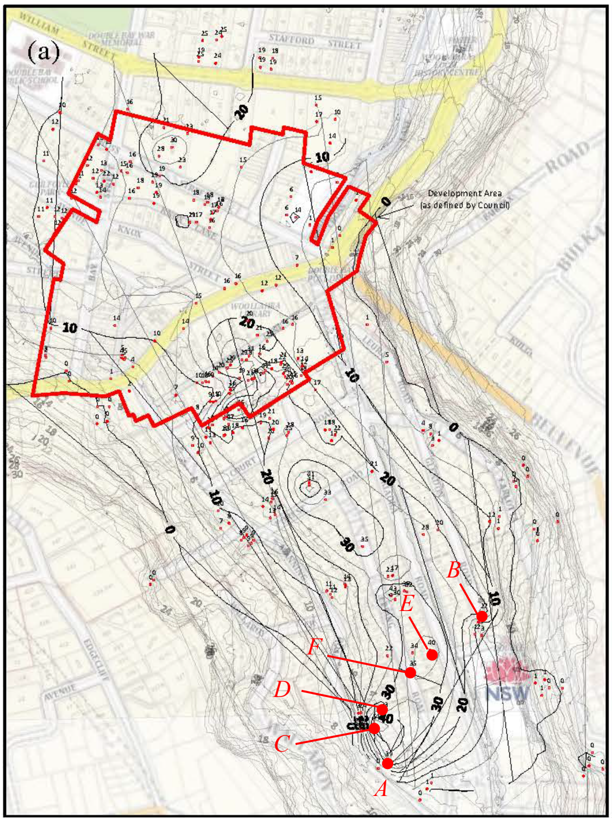
For the sandy alluvium generally encountered within the Double Bay valley, the impact of construction dewatering is expected to extend far beyond the excavation footprint. The lateral impact can extend up to some 800 m away from the excavation near the recharge point at the sandstone hillside. Further, the severity of the dewatering-induced settlement is strongly related to the ground conditions of each site. The lowering of groundwater in areas with presence of compressible upper peat soils would cause a much greater settlement than other areas without the peat layers. Consequently, a "Settlement Index Plot" in response to a fixed groundwater drawdown depth was developed based on 270 analysed settlement points, each was assessed based on available site specific geotechnical investigation data. The locations of the settlement points are shown by the red dots on Figure 3. The contours of assessed settlement index in response to an assumed 1m depth of groundwater drawdown are presented as Figure 12a. This assessed Settlement Index Plot shows similarity to the isopach map of upper peat layer thickness depicted in Figure 4b in terms of the locations of peat and the assessed settlement concentrations. The assessed ground surface settlement in response to groundwater drawdown depths for various settlement points within the area with upper peaty soil are shown in Figure 12b. The following points are highlighted with regards to the settlement plots in Figure 12:

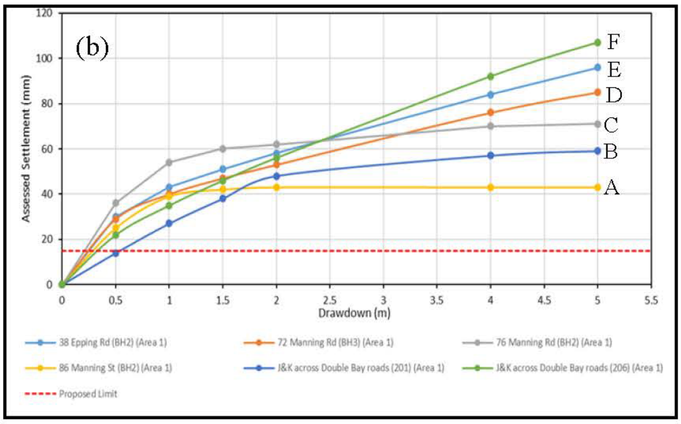
- The dewatering induced settlement for each data points was analysed based on one-dimensional (1D) method where soil layers were represented by elastic soil model with characteristic Young's moduli for granular materials; and consolidation model with compression and recompression coefficients for fine grained soils. The compressibility properties adopted for the different materials are listed in Figure 12c. These engineering parameters were derived on the basis of:
  - Available information from past studies within the area
  - Review of in-situ testing results from available geotechnical investigation data
  - Review of geotechnical laboratory testing results where available
  - Calibration against known surface settlements induced by dewatering at selected locations
- The initial water table prior to water drawdown was assumed to be at the middle of the seasonal fluctuating range, which is typically near the top of the peat layer at about 1 m below ground surface. The lowest level of the fluctuating range, on the other hand, is typically below the top of the upper peat layer.
- The portion of the upper peat layer within the seasonal water fluctuating range should have been consolidated due to past water table fluctuation. The settlement induced by the groundwater drawdown could be reasonably predicted by the re-compression ratio of the soil. In reality, this portion of the peat layer has been subjected to cyclic loading with numerous unloads and reloads in the past. This would have ratcheted down the re-compression ratio from a higher initial value during the first few unload/reload cycles. The portion of the upper

peat layer below the seasonal water fluctuating range is generally very soft to soft. The lowering of the groundwater could potentially load up the soil to its normally consolidated state.

- It is interesting to highlight that the assessed total settlement experienced at certain areas with shallow bedrock (e.g. curves A, B, and C in Figure 12b) appears to plateau beyond 2 m depth of groundwater drawdown. The main reason for this assessed behaviour is that the upper peat layers within this area are generally occurred at shallow depth and are within or above the existing groundwater fluctuation range. The further drop of water table due to dewatering will not incur additional loading to these shallow peat layers.
- For other data points located in the areas where bedrock is relatively deep, the settlement plot indicates continuing increase in settlement with the increase in the groundwater drawdown (Curves D, E and F in Figure 12b). This increase is considered to be primarily caused by compression of the lower peat/clay layer within the sand dominated alluvium.

Owning to the sandy nature of the alluvium present in Double Bay, the lowering of groundwater caused by dewatering could extend to a considerable distance away from the dewatering location. In a 3-dimensional context, the impact of dewatering can be felt over a substantial area within the valley. This is especially prominent at the southern Double Bay area where compressible upper peat soils exist. This implies that the impact of dewatering is not restricted to localised areas close to the dewatering site, but could affect the entire Double Bay valley.





(c) Material	Compression ratio CR = cc/(1+e_0)	Re-compression ratio RR = cr/(1+e_0)	Young's modulus (E') MPa
Fill	–	–	10
Very soft to soft upper peat	0.35	0.058	–
Very stiff lower peat	0.3	0.05	–
Firm to hard clay layers within the sandy alluvium	0.1	0.014	–
Very loose to loose sand	–	–	5
Loose to medium dense sand	–	–	15
Dense to very dense sand	–	–	35
Residual soil	–	–	50

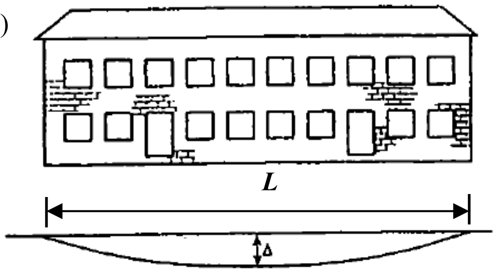
Figure 12: (a) Contours of assessed settlement index for 1m drawdown depth, (b) Examples of ground surface settlement response to drawdown depth; (c) Adopted compressibility parameters

7 REMARKS ON TOLERABLE SETTLEMENT OF RESIDENTIAL BUILDINGS

To effectively control the potential damage caused by dewatering, it is essential to assess the maximum acceptable settlement for the buildings in the Double Bay area. The settlement tolerance applicable to the existing buildings, typically one to two storeys constructed on shallow footings, can be appraised based on Australian Standards AS2870-2011 and relevant published literature, e.g. Burland *et al.* (1997, 2002) on building settlements and associated damages. Other considerations including possible past damages of the buildings, flexibility of the structures and pipe drain tolerances are also given as part of the appraisal.

Cracking in masonry walls is usually, but not always, caused by differential settlement. With reference to the schematic representation shown in Figure 13a regarding the deflection ratio Δ/L at which cracking is initiated, Burland (1997,2002) provided the limiting Δ/L values in percentage for the five categories of damage for masonry wall with zero horizontal strain (see Figure 13b). These five categories of damage with reference to walls have been adopted in the current AS2870-2011. In essence, the categories are numbered 0 to 4 in increasing severity. Normally categories 0, 1 and 2 relate to 'aesthetic' damage, 3 relates to 'serviceability' damage and 4 represents damage affecting 'stability'. Burland *et al.* (2002) have indicated that the dividing line between categories 2 and 3 damage is particularly important. If the damage exceeds Category 2 the cause is usually much easier to identify and is frequently associated with ground movement.

(a)



(b)

Category of damage	Normal degree of severity	Limiting Δ/L (%)
0	Negligible	0.05
1	Very slight	0.075
2	Slight	0.15
3	Moderate	0.3
4	Severe to very severe	>0.3

Figure 13: (a) Schematic representation of wall deflection, (b) Relationship between category of damage and limiting Δ/L for zero horizontal strain (after Burland *et al.* 2002)

By way of example, using *Δ/L* of 0.075% (maximum value for category 1) and for a building comprising full masonry construction with a typical wall length of 15 - 20 m, a differential wall settlement of 15 mm could be calculated as the maximum tolerable value before cracking become visible and is classified as being at risk of Category 2 damage.

In relation to pipe drain tolerances, the acceptance criteria of 0.1 degree for joint rotation of relatively rigid pipes such as cast iron pipe can be adopted based on CIRIA (1996). The aforementioned threshold deflection ratio of 0.075% corresponds to a rotation of about 0.043 degrees, which is deemed to be satisfactory for the allowable joint rotation of rigid pipes.

Theoretically correct and simple as it may seem, the evaluation of differential wall settlement is not always straight forward. Alternatively, total ground (surface) settlement limits could be used as an ultimate measure to control damage of buildings caused by dewatering. If the building is conservatively assumed to have no stiffness so that it conforms to the 'greenfield site' subsidence trough, then it is possible to consider y_s to be conservatively the same as the differential wall settlement. The adoption of this conservative assumption is reasonable because the surface settlement limit that is applicable to existing buildings will have to be assessed in light of possible past damage and flexibility of the buildings. Relatively rigid and damaged structures now are likely to be more sensitive to increased surface movement due to loss of stiffness, and therefore some reduction in the settlement limit might be appropriate.

8 CONCLUSIONS

Double Bay is situated in the valley between the ridgelines of Edgecliff/Darling Point and Bellevue Hill/Point Piper, occupying the low elevation harbour front area. The alluvium within the valley, comprising sand with minor silts, clay and peat, forms a highly productive water table aquifer, which is underlain by the less permeable fractured bedrock aquifer. The water table fluctuates in response to seasonal variations in rainfall, with up to 1 m of variation observed in monitoring bores constructed within the alluvium. A calibrated regional groundwater model has shown that cumulative impacts associated with multiple subterranean structures (basements) could lead to mounding and lowering of the water table over the long term, albeit this is generally estimated to be controllable.

For the sandy alluvium generally encountered within the Double Bay valley, the impact of construction dewatering is expected to extend far beyond the excavation footprint. Further, the severity of the dewatering-induced settlement is strongly related to the subsurface conditions of the site. The lowering of groundwater in areas with the presence of compressible upper peaty soils would cause a much greater settlement than other areas without the peat layers. From the compilation of 270 boreholes and CPT investigations conducted in the past, a "Settlement Index Plot" was developed that indicates the different degrees of susceptibility to dewatering-induced ground surface settlements for the different areas within the Double Bay valley.

To effectively control the potential damage of existing buildings caused by dewatering (typically one to two storey structures supported on shallow footings), a ground surface settlement limit can be considered based on AS2870-2011 and relevant published works by Burland et al. (2002). Other considerations including possible past damages of the buildings, pipe drain tolerances and historic groundwater level fluctuation have also been given as part of the appraisal process.

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