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Settlement of Soft Marine Sediments at Sydney Airport

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Summary The paper reviews the historical development of the western area of Sydney Airport and particularly the early soil investigations to determine the deformation characteristics of the soft clay which underlies the aprons and terminal. It also looks briefly at the settlement of the aprons over a 20 year period to ascertain whether the movements which are being experienced are fundamentally due to consolidation or creep. Finally, it presents some selected data on settlement and creep coefficients derived from recent testing.

1. INTRODUCTION

In many instances airports have been built adjacent to harbours and bays on areas of reclaimed land. Sydney airport is no different in this respect being constructed on the foreshores of Botany Bay in an area where deep alluvial deposits are present.

Similarly to many other airports (Schiphol, San Francisco, Hong Kong, Changi, Brisbane etc) Sydney is underlain by a soil sequence comprising soft clay which is susceptible to settlement due to primary consolidation and creep. This settlement is sometimes as high as hundreds of millimetres and there is a requirement to make reasonably accurate estimates of settlement and to devise strategies to minimise the problems associated with post construction settlement.

This paper focuses on experiences at the International Terminal at Sydney Airport and uses the settlement records which are available to confirm appropriate parameters for analysis of settlement.

2. HISTORY OF SYDNEY AIRPORT

Sydney Airport occupies an area of about 800 hectares on the northern shore of Botany Bay. Major development commenced in the early 1950's when Cooks River was diverted to enable construction of two orthogonal runways. A further phase of development was initiated in the mid 1960's with the extension of North-South runway into Botany Bay, diversion of Alexandra Canal and the first phase of the development of the International Terminal area on the western perimeter.

From a settlement viewpoint the main sequence of events which characterised development of the International Terminal area are:

- the original level was mostly at or below RL 0 and was therefore often inundated by tides and floods;
- the site was filled with sand dredged from Botany Bay and because settlement was recognised as a major problem it was surcharged to a height of 2 m for 2 years;
- when the surcharge was removed in 1967, the terminal and apron construction commenced;
- settlement recordings were first made on the finished aprons and on specially constructed monitoring gauges in 1971 and were continued intermittently with the latest measurements made in February 1998.

3. GEOLOGICAL SETTING

Maps and notes prepared by the NSW Geological Survey (1983) for Sydney indicate that the site is underlain by Quaternary alluvium or manmade filling. Quaternary sediments in the area may be up to 80 m thick and overlie an eroded bedrock comprising Hawkesbury sandstone into which old river channels have been incised (Geol Survey 1963).

The Quaternary alluvium around Botany Bay is predominantly of marine origin, deposited in an open tidal estuarine environment. The existence of soft mud deposits at the International Terminal site is presumably due to deposition of fine grained material in swamps formed by temporary aeolian sand barriers around the foreshores of Botany Bay.

4. SOIL LITHOLOGY

The soil lithology beneath the International Terminal is variable due to the depositional environment and erosional process (Douglas 1998) but in general terms it can be described as follows:

- Sand filling dredged from Botany Bay generally in a medium dense to very dense condition depending upon whether surface compaction has been carried out.
- Soft organic silty clay up to 7.5 m thick. In places, this deposit is now firm due to the ongoing consolidation.
- Dense or very dense silty sand up to 3 m thick. This layer has been utilised as a founding layer for enlarged base piles for the construction of the Pier C extension to the terminal.
- Stiff or very stiff inorganic sandy clay.
- Relatively dense, fine to medium grained sand, varying from about 0.5 m to 4.0 m thick.
- Very stiff inorganic clay which is possibly residual in origin.
- Bedrock (Hawkesbury Sandstone).

5. SOIL PROPERTIES

The University of Sydney (1968) undertook a comprehensive investigation of soil properties in 1968 to estimate settlement under the proposed airport extensions. Since that time Douglas Partners (1985, 1988, 1989a, b, c, d, 1990, 1991, 1996, 1998) have carried out further work to characterise the thickness and properties of various soil layers.

A considerable amount of testing has been performed to determine the deformation and strength characteristics of the soft organic silty clay layers and the results are summarised in Table 1. The thickness of the deposits around the International Terminal is quite variable, being mostly in the range of 2 m to 6 m but in places up to 9.5 m. Accordingly, it is not possible to be specific about settlement but simply to calculate it at each test location and from these calculations, attempt to identify possible future trends in movements.

5.1 Coefficient of Volume Compressibility (m_v)

The Coefficient of Volume Compressibility has been traditionally determined from oedometer tests but because of possible remoulding and changes in stress state during sampling and preparation of laboratory test specimens, the void ratio/log effective stress curves determined from the oedometer tests are believed to differ from the field stress-compressibility relationship. The University of Sydney (1968) suggests that the effect of the sample disturbance is to reduce the slope of the measured value of m_v. Hence calculations of settlement made using oedometer test data could possibly be too low, although the present data does not show that this is consistently the case.

The Coefficient of Volume Compressibility (m_v) measured in the oedometer tests is consistent ranging from about 0.12m²/MN up to 2.98m²/MN with a median value of approximately 0.4m²/MN and most values lying between about 0.2 and 1m²/MN.

The cone penetration test data can also be used to derive values of m_v. Sanglarat (1972) indicates that the stiffness of clay can be estimated using the relationship

$$E = \alpha\, qc \qquad (1)$$

Table 1. Results of laboratory testing.

TEST No	OEDOMETER CONSOLIDATION AVERAGE VALUES		TRIAXIAL SHEAR STRENGTH		CREEP COEFFICIENT
	Coefficient of compressibility m_v (m²/MN)	Coefficient of Consolidation C_v (m²/year)	Undrained Cohesion (kPa)	Friction Angle (degrees)	C_α (per log cycle of time)
2223/14.5			18	3	
2225/3.5			24	27	
2225/14.5	0.29	2.4	80	5	0.0016
2228/3.5	0.92	3.6	16	4	0.0076
2228/11.5	1.93	0.13			0.0086
927/2.0 (2)	2.5	0.98	22	7	0.0071
927/4.0 (2)	1.16	0.52			0.0098
927/4.5 (2)	0.96	1.9			0.0070
928/2.0 (2)	2.98	0.60	28	1	0.022
DP Qantas Apron (3)	0.19-0.58				
DP International Terminal (4)	0.12-0.82	0.35-4.7			
DP International Terminal (5)	0.19-0.58				
DP Northern Pond (6)	0.17-0.58				
J&K (7)	0.37-0.63	0.13-0.31 generally			
University of Sydney (8)	0.58-0.73	0.17-0.50	24-48		0.014-0.022

Notes: (2) DP Report No 10900D1, December 1997
(3) DP Report No 11555, June 1989
(4) DP Report No 10900, October 1989
(5) DP Report No 10900D, April 1997
(6) DP Report No 10900D, June 1997
(7) J&K Report No 6522, April 1991
(8) Uni of Syd. Report No S86, June 1968

where E = modulus of elasticity (MPa)
α = correlation factor
qc = cone resistance (MPa)

The value of α varies from about 2 to 5, depending upon the stress history and the sand content of the clay deposit. Data to present indicate that a figure of 3 or 4 is appropriate for the airport site. For this study a figure of 3 has been adopted for clays with cone resistances of less than 0.5 MPa and 4 for cone resistances of between 0.5 MPa and 1.0 MPa.

The relationship between modulus of elasticity (E) and coefficient of volume compressibility (m_v) is given by

$$m_v = \frac{(1+\nu)(1-2\nu)}{(1-\nu)E} \qquad (2)$$

where ν = Poissons ratio of the soil which for normally consolidated clay is assumed to be 0.3.

Therefore

$$m_v = \frac{0.743}{\alpha\, qc} \qquad (3)$$

has been used to estimate the compressibility of clay soils from the cone penetration testing. The 74 cone tests gave results in the range of 0.19 to 0.83 m²/MN with an average of about 0.26 m²/MN.

This average is similar to values reported elsewhere for the soft organic silty clay layer but appears to be slightly lower than the median value of the oedometer tests.

5.2 Coefficient of Consolidation (C_v)

In order to estimate the time rate of settlement under the influence of loading it is necessary to obtain values of C_v. The oedometer tests results range from 0.13 m²/year to 3.6 m²/year with a mean value of 1.1 m²/year. The interpretation of the data, however, is sometimes difficult due to the fact that the end of the primary consolidation stage is often unclear.

Recent long term oedometer tests (Douglas Partners 1998) give a clear indication of the point at which 100% consolidation occurs and from these data the C_v value is consistently less than 1 m²/year. This accords with the values of 0.5 m²/year estimated by the University of Sydney (1968).

Another method of assessing the consolidation-time characteristics of the soft organic silty clay is to utilise field settlement data. Fortunately, settlement recordings have been made at many points on the Northern and Southern Aprons at the Airport for over 20 years from 1971. These data are quite useful in backcalculating the most probable coefficient of consolidation of the soft organic silty clay. It should be noted, however, that while loading of the soil commenced in about 1964, the pavements were not completed until March 1971 so there are no comprehensive records of settlements for the first seven years.

If settlement from a number of typical points is observed, some evidence for C_v values less than 1 m²/year is forthcoming. For example, at point N8 on the northern apron the recorded settlement from 1971 to 1998 was 140 mm. At this location the thickness of soft clay is estimated to be about 4.0 m. If the Coefficient of Consolidation was 0.5 m²/year and only one way drainage was occurring, 95% consolidation would have been completed in about 27 years, meaning that all the recorded settlement was due to consolidation. The shape of the settlement - log time curve (in Figure 3) for point N8 does not show the break in slope that is normally observed when primary consolidation is completed and creep settlement commences. From this it is concluded that all the settlement recorded so far may be due to primary consolidation. This implies a coefficient of consolidation of less than 0.5 m²/year.

Alternatively, if a C_v value of 2 m²/year is assumed then full consolidation of a 4.0 m thick clay layer should have occurred in about seven years, after which any settlement would be due to creep. The 140 mm settlement at N8 which was recorded between years 7 and 28 (1971-1992) would then imply a creep coefficient of 0.026, which is much higher than estimated from various methods (see Table 1). Most of the recorded settlement is therefore probably due to primary consolidation which means that C_v must be less than 2 m²/year.

Another source of data which indicates coefficient of consolidation of 0.4-0.8 m²/year is the testing undertaken for Baulderstone Hornibrook for the third runway (Douglas Partners 1998). In this runway investigation, two oedometer tests were carried out to assess the potential settlement under the loading of the dredged sand filling. It was concluded that a C_v of 0.6 m²/year should be adopted for design purposes.

Having assessed all of the above information, we consider that the Coefficient of Consolidation used to calculate the time rate of settlement of the soft organic silty clay should be taken as 0.5 m²/year. Whilst this is a simplification, values determined from tests on single samples varied by up to one order of magnitude depending upon the stress range. Also it is sometimes very difficult to select the end of primary consolidation in oedometer tests so more emphasis has been placed upon back calculated values than those determined from laboratory tests. Furthermore fine sand lenses can effect the drainage rate in small diameter laboratory samples but these may not be continuous in the field.

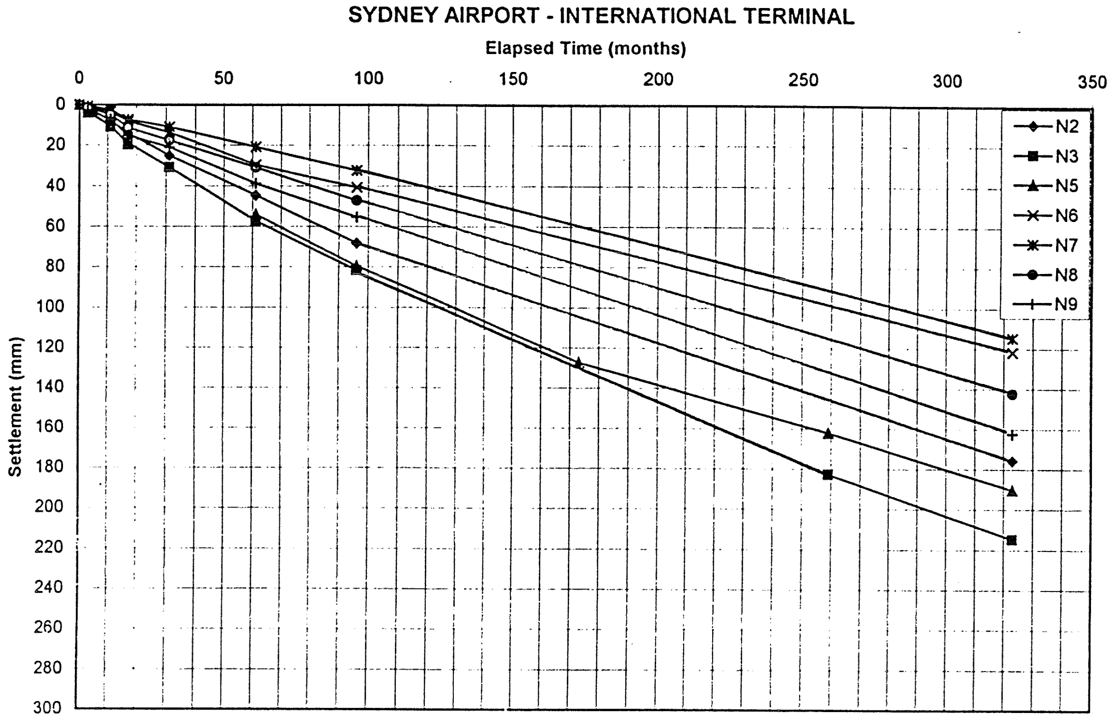

Figure 1. Settlement on Northern Apron at Sydney Airport

5.3 Creep Coefficient (C_α)

The phenomenon of creep has long been recognised as a source of significant amounts of settlement in soft alluvial soils. The causes of creep are poorly understood but are thought to be principally due to the viscous properties of the clay soils. Mitchell (1976) reports that the relationship between creep strain and the logarithm of time may be linear, concave upwards or concave downwards and that a linear relationship is assumed only as an engineering simplification. Mitchell (1976) also demonstrates that the creep strain rate is stress dependent and is governed by the stress history of the soil. This point is of major importance when estimating creep settlement because this cannot be done with any confidence unless the past stress history of the soil is considered.

The creep coefficient (C_α) was measured in long-term oedometer tests for a recent investigation at the Airport (Douglas Partners 1997c) in which a total of seven tests were conducted. Figure 2 shows the results of the testing with C_α plotted as a function of m_v values which were derived from cone penetration tests undertaken at the same locations as the oedometer test samples.

Figure 2 and Table 1 indicate creep coefficients typically in the range of 0.0016 to 0.0098, with the majority of values for soft organic silty clay being around 0.008, or 0.8% of the thickness of the clay deposit for each log cycle of time. This is lower than the 0.015 recorded for the third runway but 0.015 lies within the range of values recorded for this study. There is clear indication that there is a wide range of C_α values possibly depending upon past stress histories.

The University of Sydney investigation (1968) found C_α values in the range of 0.014 to 0.022 for the soft organic silty clay. This, however, was for samples obtained in 1966 before much of the filling and surcharging was completed so it could be expected that in the intervening 30 years consolidation and creep of the clay may have lowered its compressibility and hence the applicable creep coefficient.

Another way of estimating the creep coefficient is to utilise the settlement data taken for the Northern Apron over a period of about 20 years and to allocate the appropriate portion of this settlement at each point for primary consolidation and creep. The settlement recordings for six such points are shown in Figure 1 and summarised below in Table 2.

Table 2. Recorded settlement - Northern Apron.

Point	Estimated Clay Thickness # (m)	Recorded Settlement (mm) 1971-1992	Approx time for 95% consolidation (years)		Calculated Cα from Settlement after 95% consolidation	
			one-way drainage	two-way drainage	one-way drainage	two-way drainage
N3	4.9 (5.0)	183	54	13.5	*	0.0174
N4	5.0 (3.1)	90	42	11	*	0.0054
N5	6.5 (3.1)	160	72	18	*	0.0038
N6	8.7 (2.7)	125	128	32	*	*
N8	4.0 (3.6)	120	36	9	*	0.0260
N9	3.7 (3.6)	135	31	7.7	*	0.0270

Notes: 1. Assume settlement started in 1964, recording of settlement started in 1971 and last reading in 1998 - 28 years since settlement started
2. Assume $C_v = 0.5m^2$/year
* Primary consolidation not yet completed
( ) from University of Sydney contour plan
\# from recent CPT data

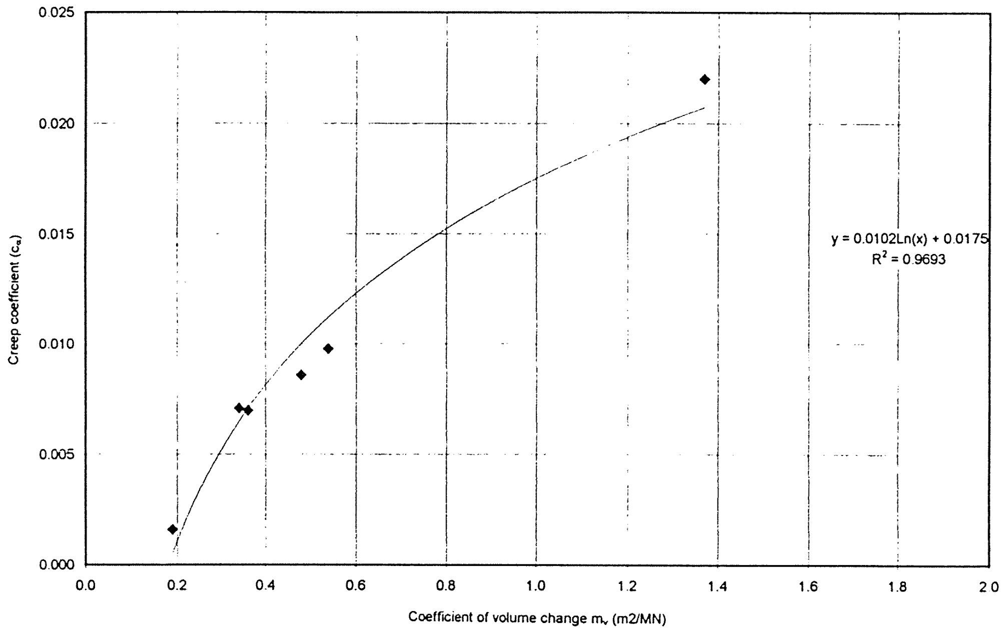

Figure 2. Creep coefficient as a function of m_v.

In order to carry out the analyses, it is first necessary to estimate the magnitude of consolidation settlement and then from the total settlement recorded deduce the creep component. However, to do this, a judgement has to be made on drainage conditions for the consolidating layer. Table 2 shows the two possible alternatives and the creep coefficient that results from each assumption.

Two way drainage is unlikely because this conflicts with the known geology of the site where the soft organic clay overlies clay or a non-continuous dense sand layer and downward drainage of the soft clay appears to be unlikely. Furthermore the assumption of one way drainage produces settlement values which are consistent with observations.

Using this approach to estimate the creep coefficient is clearly limited because of the assumptions which have to be made with respect to drainage of the consolidating layer and the number of log cycles of creep which have occurred since the virtual completion of consolidation settlement. In compiling the data it has been assumed that the first log cycle of creep would occur in the first ten years, after which the second log cycle would occur between 10 and 100 years.

Further limitations on this type of analysis are also illustrated by points N3 and N4 which are ostensibly underlain by similar thicknesses of clay and yet total settlements since recording commenced have been

183 mm and 90 mm respectively. Realistically the settlement should be roughly the same but undoubtedly the initial compressibility plays a major role in the observed variations.

Another shortcoming with this analysis is being able to accurately estimate the thickness of soft clay so that the proportion of each settlement curve resulting from consolidation settlement and creep can be estimated. There is considerable difference in the two interpreted thicknesses from contours produced by the University of Sydney (1968) and from recent CPT data, with the recent CPT data considered to be more reliable because of the greater number of tests performed.

6. SETTLEMENT

A detailed analysis of the theoretical and actual settlement is not possible because the original predictions made by the University of Sydney (1968) were for 5 borehole locations and long term settlement recordings have been made near one of these points only. However, some general trends in settlement can be reviewed in terms of the thickness of the organic silty clay to see if the actual settlements are greater or less than anticipated.

In addition recent work by Douglas (1998) has involved the prediction of settlement over the next 100 years. Table 3 shows a summary of all these settlement predictions and recordings.

It is not possible to get a direct comparison between predicted and actual settlement but at least some general trends are evident based on recordings made at points with similar clay thicknesses. Overall the trend seems to be that the settlement has been under predicted for the long term but in the initial post construction years for the thicker clay layers the actual settlement was less than expected. This is thought to be due to the effect of the 2 m surcharge which was in place for about 2 years. Figure 3 shows that the rate of settlement is now increasing with log time. Indeed perusal of the data indicates that the settlement has been nearly linear with time since recording began (see Figure 1).

7. CONCLUSION

Some general conclusion which can be made from the recorded settlements are:-

- where the soft marine silty clay layer is more than about 4 m thick, consolidation settlement is still occurring. Figure 3 appears to support this conclusion;
- the use of a 2 m surcharge for 2 years not only reduced total post construction settlement but reduced the rate of settlement for about 5-7 years due to rebound;
- creep coefficients of up to about 0.0175 are applicable based on the data in Figure 2 but are mostly in the range of 0.005 to 0.01;
- consolidation settlement will probably continue for many more decades because the soft clay is up to about 10 m thick in places. In these circumstances total settlements are now predicted to be much greater than expected in 1967.

Despite the best attempts at the time of the original investigation and a considerable amount of detailed laboratory test, settlement predictions were not very accurate, probably because of the poor understanding of creep. The latest investigations and settlement recordings have given some hope that future forecasts may be better.

Table 3. Summary of settlements.

Clay Thickness (m)	Elapsed Time (years)	Predicted Settlement (m)	Recorded Settlement (m)	Point
3.0#	2	0.003	0.010	N5
	5	0.003	0.054	
	10	0.003	0.080	
	∞	0.003	0.190 at 30 years	
6.0#	2	0.047	0.025	N3
	5	0.098	0.057	
	10	0.134	0.090	
	∞	0.171	0.215 at 30 years	
3.6ϕ	10	0.021		
	20	0.027		
	100	0.037		
6.5ϕ	10	0.047		
	20	0.062		
	100	0.098		

by University of Sydney in 1967
ϕ by Douglas Partners for settlement from 1998

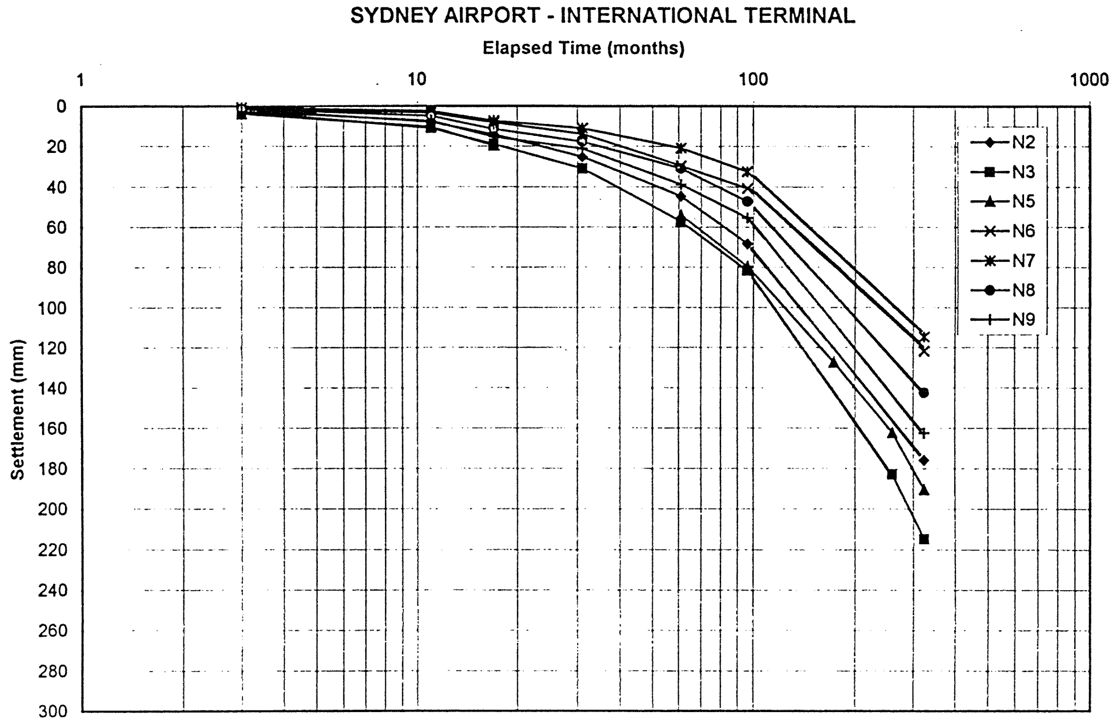

Figure 3. Settlement on Northern Apron at Sydney Airport.

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