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Modified Soil Mechanics from Practice to Theory

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ABSTRACT

A brief review of the history of developments in classical soil mechanics is made. It is reminded that the development of soil mechanics had a very strong input from the experimental side both the laboratory and field works. Also emphasized is the need for every country to develop their own texts to suit the soil conditions, which are found abundant in their region; this will then strengthen our university education in Geotechnics. While the use of various types of computer softwares has become a necessity in our day-to-day life, they will only give meaningful results if and only if the appropriate soil properties are used and the correct mode of analysis is performed. Case histories are presented from the well-documented Muar clay test embankments and the reservoir of excellent data available on major projects in the Bangkok Plain.

KEYWORDS

Historical background, critical state soil mechanics, soil properties and characterization, finite element analysis, test embankments, excavations, piled foundations.

INTRODUCTION

The development of Soil Mechanics and Geotechnics has gone through various phases. The early contributions include, Coulomb's Law of shear strength, Mohr's circle of stress, Rankine's earth pressure theory, Darcy's Law for the permeability of soils and flow of water, Boussinesq solution for stress increment due to point loads, plasticity theories and bearing capacity of soils, Atterberg limits, effective stress principle and theory of consolidation and Proctors' contribution on compaction of soils. These contributions were the corner stones for the development of our subject in education and practice and are still taught to all our under-graduates as a first degree Course in Soil Mechanics.

The First International Conference held in Harvard University under the initiation of Arthur Casagrande was one of the most successful conference in soil mechanics and foundation engineering and the proceedings of this conference still illustrate that much of the discussions and research presented in that conference are still the subject of research and debate, whether they relate to basic soil mechanics, piling works and foundations, earth dam, stability of slopes, earth pressures and earth retaining structures, ground improvement works and similar other areas of current interest. Following a dull period in the development of soil mechanics and foundation engineering, rapid progress took place after the Second World War in all phases of Geotechnics in both theory and practice.

In chronological order, in late forties and early fifties, there was a great interest in the development of laboratory shear testing and consolidation test devices such as the direct shear apparatus, triaxial apparatus, various form of Odeometers. Emphasis was also made in good quality undisturbed sampling to obtain samples as close to the in-situ states to conduct appropriate tests and to obtain relevant soil parameters for geotechnical design and construction. In parallel, instrumentation and field tests were also developed to monitor the progress in large scale projects such as the Chicago and Oslo subways and others from which empirical earth pressure diagrams and expressions for ground upheaval, among other similar correlations were established. These were indeed remarkable contributions, which are even in use at current times in the twenty first century.

Late forties and early fifties were the best time for the fundamental research in soil behaviour with studies related to the establishment of the mathematical description of the stress strain behaviour and strength of soils. Unified stress strain theories were developed by the Cambridge and Imperial College researchers which incorporate the so-called critical state concept and strain hardening and strain softening plasticity theories with associated and non-associated flow rules and plastic potentials and yield surfaces. The fifties and sixties also saw developments in the limit state analysis and refined contributions were made on bearing capacity of shallow and deep foundations, stability of slopes, earth pressure calculations as well as settlement computations.

The next decade from seventies to eighties show an impetus in trying to develop in-situ tests for a better understanding of the soil behaviour which otherwise cannot be obtained from laboratory tests especially on soils where undisturbed sampling is difficult. Thus we saw the development of various forms of cone tests including piezo-cones, dilatometers, and pressuremeters. Important laboratory equipment, which was developed in the late sixties and thereafter, is the centrifuge by the Cambridge and Manchester group of soil mechanics. Since then centrifuges have sprung up like mushrooms in Japan, USA, and many European countries, Singapore, Hong Kong, Australia and Canada to name a few countries. The application and potential of the centrifuge is enormous and at the same time it is a luxury to have in most universities as every problem to be solved will need its own development in pieces of equipment and instrumentation which demands sophisticated workshops and technicians. Offshore industry has also contributed to the development of offshore soil mechanics and various types of fixed platforms and gravity type platforms. The behaviour of coral deposits and calcareous sands have also been studied extensively.

From the mid eighties to present, the emphasis in Geotechnics has turned to the use of computer softwares of various degrees of sophistication. This is now having a tremendous impact in our profession and in our education. Of course the advantages of the use of these softwares are manifold and we must educate our graduates in the use of such softwares. The sad part and the most damaging aspect is these softwares are now used in an indiscrete manner by majority of our profession who are not well aware what the softwares can do and what they cannot do; they are blindly used without an understanding of their limitations.

We have seen the enormous achievements and developments in our discipline and the profession. Some of the other damaging factors will now be described. The traditional soil mechanics was developed based on our understanding and formulations of the behaviour of sedimentary soils, which are saturated. This was so as the earlier civilization and growth took place along the coastal side of most countries and these terrains are all on sedimentary soils. Almost all the textbooks that we have are only applicable to the behaviour of sedimentary soils and more so for saturated conditions. Additionally, these books are mainly written by authors from UK, USA, Canada etc and they tend to concentrate on their own soil conditions and projects. The other factor is soil mechanics borrowed a lot from structural mechanics, which mainly deal with one phase material instead of a three phase material like soil with solid, liquid and air phases. The confining pressure have no effect on the behaviour of metals, while for a material such as soft clay, the voids ratio depend entirely on the confining consolidation pressure and the voids ratio and porosity have tremendous effect on the engineering properties of all soils. We also have inherited this historical conflict of the use of total stress analysis with total stress strength parameters on the one hand and the use of effective stress analysis with effective stress strength parameters on the other hand. Most people nowadays use a press button type of knowledge with our commercial softwares and is often confused with the appropriate use of the buttons. Most of the times some academics take this as an insult in their training when one try to make some sense out of this anomaly.

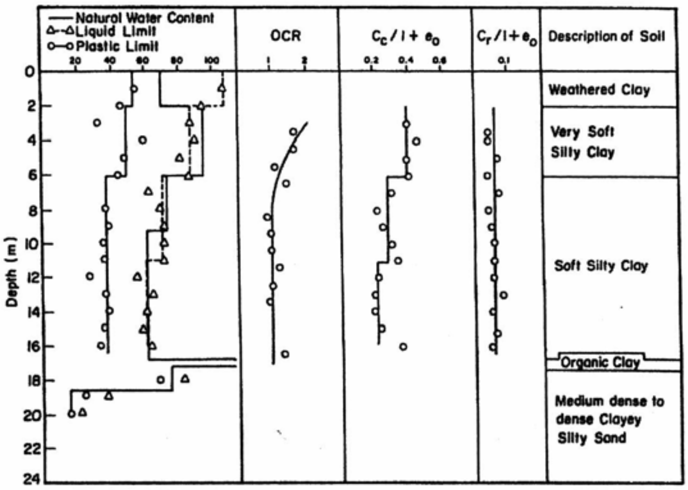
Developments in Engineering Geology were rapid from sixties and in Rock Mechanics perhaps a little later than that. When we move from sedimentary soils to residual type of soils or soft rocks and laterites etc, our knowledge as we gain from our traditional textbooks seem not of great help as these textbooks have little to offer in Engineering Geology and Rock Mechanics. But engineers who are trained with our traditional sedimentary type of soils are beginning to handle the residual soils, laterites etc in a manner similar to what is described in the standard text. Most agonising factor is even problematic soils such as expansive soils; dispersive soils, collapsible soils and others are being looked upon with standard soil mechanics textbook approach. Each country must to some extent concentrate on the soil conditions in their own country and develop a manual or monograph or text which dwells more on the practice of geotechnics relevant to such soil conditions. Notable contributions are experience of Kenny Hill Formations in Malaysia and problems with limestone terrains in Kuala Lumpur, soft Bangkok clay and the studies at AIT, Residual Soils and the work at GCO in Hong Kong earlier under the leadership of Ted Brand, the soil conditions in Singapore as delineated by the late Tan Swan Beng when he was the Director General of the Public Works Department of Singapore, the soil conditions in Taipei as studied and published by Moh et al. These are indeed remarkable contributions.

Another factor of great emphasis nowadays is the construction of deep basements and underground structures for Mass Rapid Transit Stations (MRT) etc in urban environment wherein the ground movements during the construction phase are restricted to very small order of magnitude to avoid any adverse effect on the nearby existing structures. Such activities call for a small strain behaviour wherein the stress conditions are far away from the failure states and are very close to the in-situ stress conditions. Thus we are more and more driven by a deformation based design criterion rather than the strength based design. This is also applicable to piled foundations where the settlements are restricted to very small values. In the early days the safety of the design is assured by an adequate factor of safety, which make the stress conditions to fall far below the failure states. This in a sense also restricts the movements as when a factor of safety of two is used for an embankment in soft clay, the strains in the soft clay region falls to values, which are rather small.

Case histories will now be presented to illustrate the use of the total stress and effective stress analysis; large strain and small strain analysis, coupled analysis, which utilizes critical state type of soil models.

MUAR CLAY TEST EMBANKMENTS

Good quality full-scale field tests data are very seldom to find in many countries. Bjerrum always believed in large-scale field tests and also in instrumenting the major projects to obtain the field performance and to refine our design and construction procedures. At the Asian Institute of Technology many full-scale field tests were performed on embankments with and without ground improvement as initiated by Moh, Brand and Nelson and followed by others. In a similar manner, the Muar clay test embankment (as shown Fig. 1) was very popular and the data were used by a number of AIT students including Tan Yean Chin in Malaysia. The Malaysian Highway Authority of Malaysia must be congratulated for initiating such an interesting series of full-scale field tests.



Elevation (mRL)		Liquid Limit w_L (%)	Plastic Limit w_p (%)	Natural Water Content w_n (%)	Plasticity Index	Grain Size (%) Clay	Silt	Sand	$\frac{C_c}{1+e_o}$	$\frac{C}{1+e_o}$	Preconsolidation Pressure P_c (KPa)
+2.5 mRL											
+0.5	Weathered Crust	108	55	70		42	57	1	.24	.04	110
-5.5	Very Soft Silty Clay with Decated Leaves and Roots	90	40	100	50	48	52	0	.48	.04	40
-15.3	Soft Silty Clay with Traces of Shell Fragments Occasionally Sand Lenses	80	30	60	50	40	60	0	.31	.04	60
-15.9	Peaty Soil										
-19.9	Sandy silt / clay with Organic Matters					22	43	35			
	Dense Medium to Coarse Sand with Gravels SPT N=21 to 37										

Figure 1a: Soil profile at Muar test embankment site

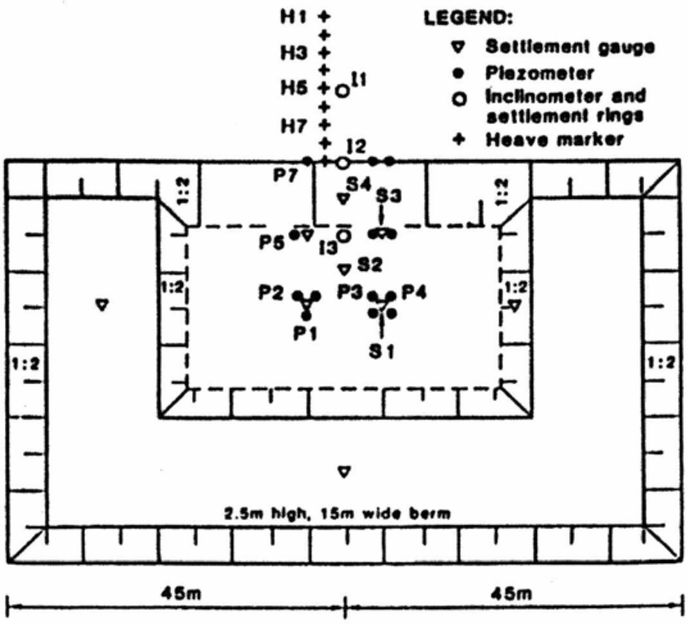


Figure 1b: Plan of the Muar test embankment showing field instrumentation

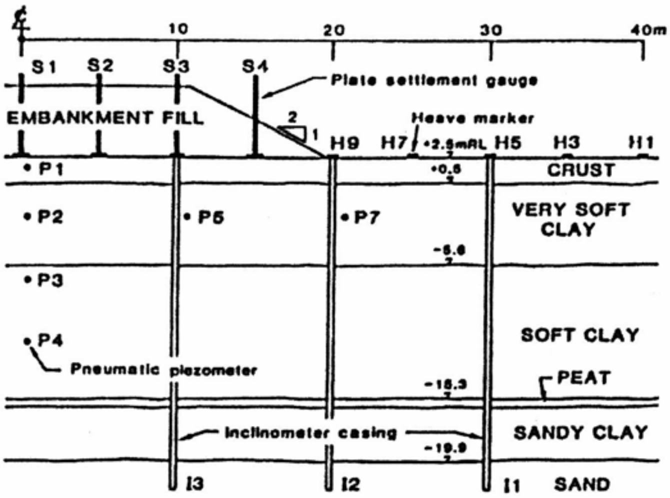


Figure 1c: Cross section of Muar clay test embankment showing field instrumentation

CLASS A PREDICTION OF MUAR CLAY TEST EMBANKMENT

The well documented publications on the behaviour of the residual soil test embankment built to failure indicated how the performance of such a simple field problem can deviate from the known behaviour of sandfill test embankments and the deficiencies in the traditional text book type of soil mechanics. The inclusions of the strength of well compacted residual soil fill material, seem to offer good tensile strength characteristics and prevented the formation of tensile cracks at the base of the embankment. Most experts also made poor predictions of settlements pore pressures and lateral movements. Some data from the predictions as made by various authors is presented in Figs. 2 to 5. The CRISP program as based on the critical state soil mechanics is superior in predicting the coupled behaviour of undrained and consolidation phenomenon in these embankments.

In a recent study made on a number of soft clay deposits in southeast Asia by the Port and Harbour Research institute and the National University of Singapore, the presence of Diatoms in Southeast Asian Clays with volcanic origin seem to increase the permeability manifold and the behaviour just after construction approximate to drained conditions rather than the traditional assumption of undrained mode. Lim Thian Loke, a Singaporean student at AIT spotted the presence of Diatoms in some clays in Southeast Asia and cautioned such abnormal behaviour as early as the eighties. This was also recently confirmed by Wesley from his study of the consolidation characteristics of Indonesian and New Zealand soft clays, which have volcanic origin.

Further studies conducted at AIT on the creep behaviour of the Muar clay test embankments in which continuous undrained creep occurred with the increase in lateral deformation indicate that undrained creep in soft clays due to high embankments is another area in which the traditional textbook soil mechanics find little application. In places where high embankments are constructed with residual soils such undrained creep plays an important role.

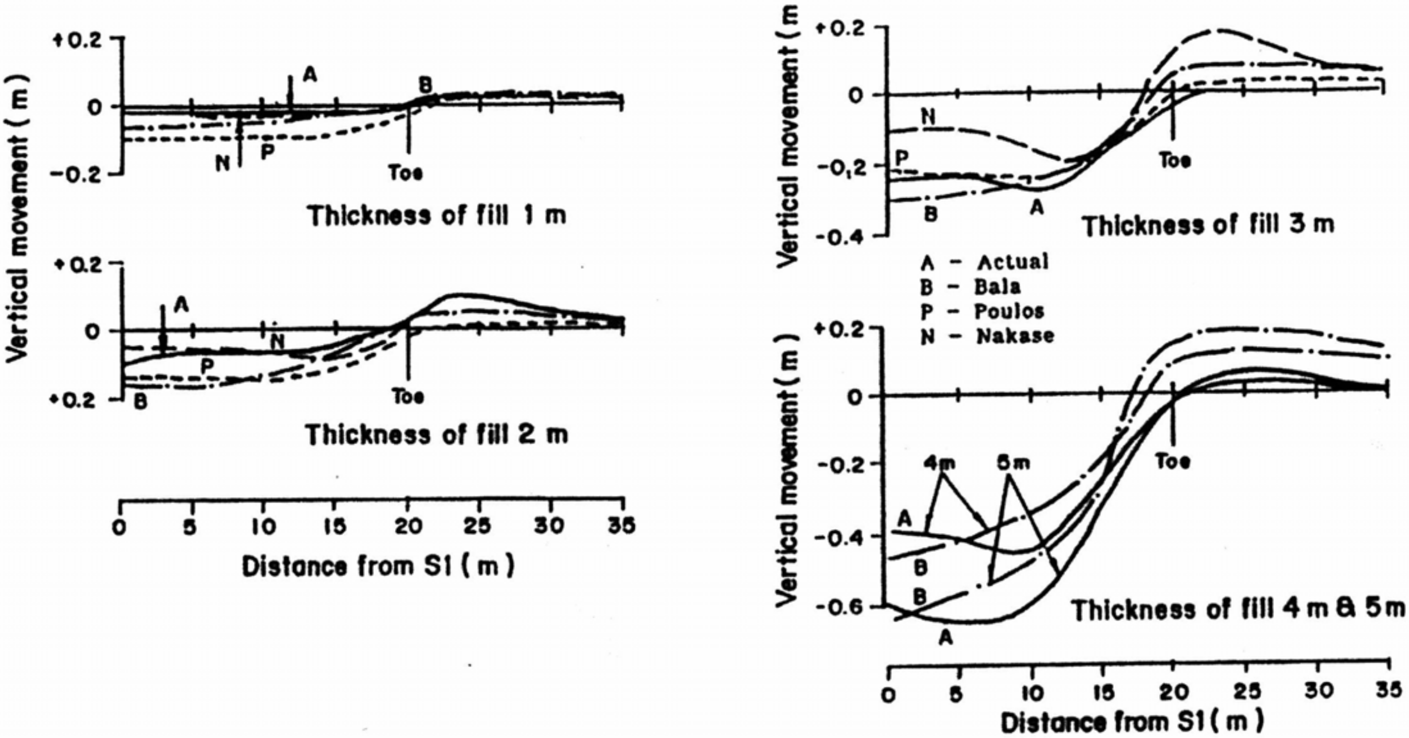


Figure 2: Actual and predicted settlement of Muar test embankment

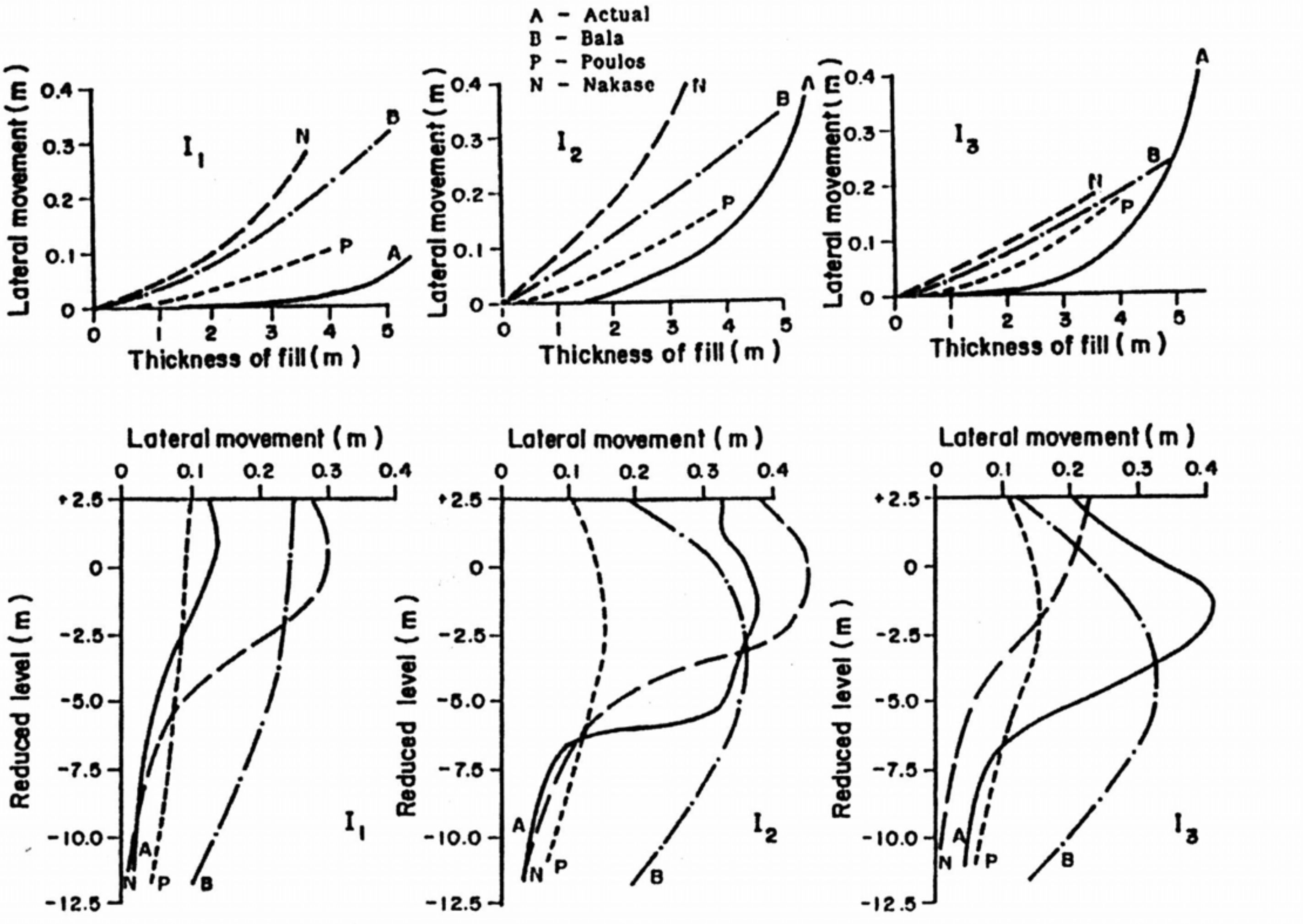


Figure 3: Measured and predicted lateral movement of Muar test embankment.

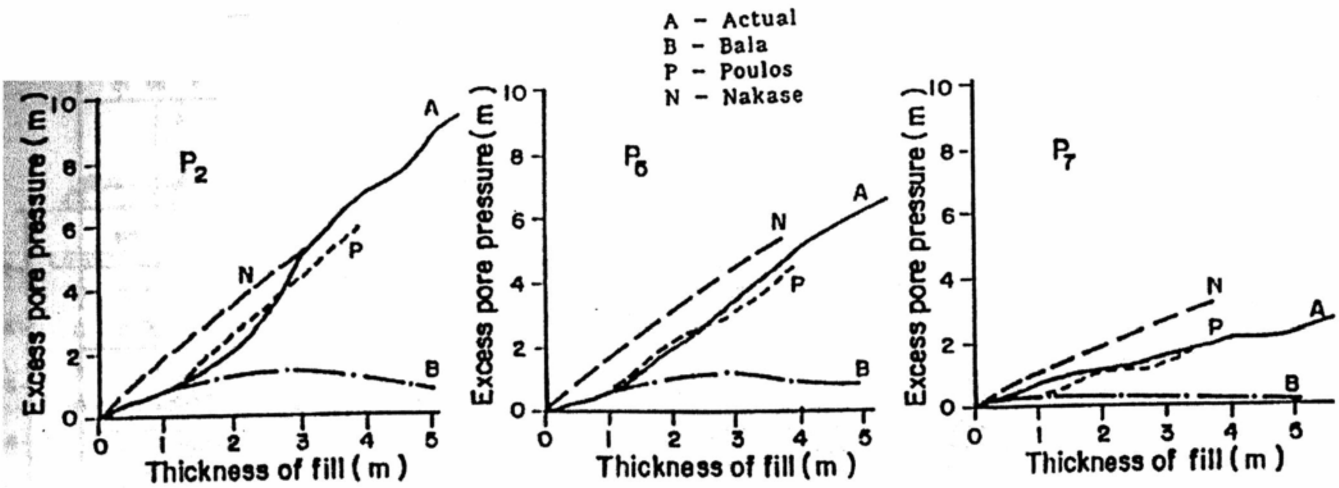


Figure 4: Measured and predicted pore pressure dissipation of Muar test embankment.

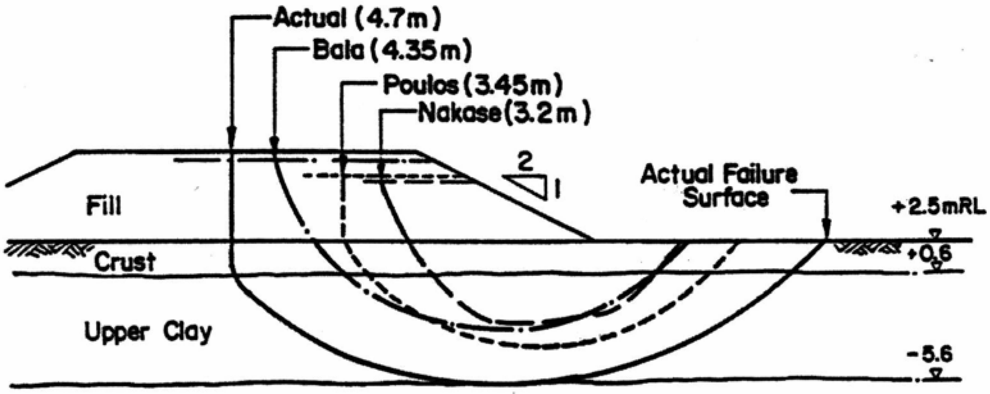


Figure 5: The actual and predicted failure surfaces of Muar test embankment

The Muar clay test embankments also illustrated that the PVDs available in the market for accelerating the dissipation of pore pressures are not 100 percent effective as expected by classical theories of Barron and others (see Fig. 6). This led Hansbo to investigate non-Darcian Flow in clays, Indraratne to continue the study of smear effects in University of Wollongong, and also possible well resistance in the drains.

The Muar clay test embankments also showed the defects in using sand compaction piles, piled embankments and the use of electro-osmosis. We need to introduce such behaviour of soils and analytical methods that deviate from traditional approach in our new editions of textbooks. Also, every country must adopt their teaching in soil mechanics to be in line with the soil conditions they predominately have in their country.

FULL SCALE FIELD TESTS WITH PVD

The Asian Institute of Technology was associated with the construction of a second Bangkok International airport (SBIA) now for nearly thirty or more years. The amount of geotechnical data collected at this site is one of the most comprehensive sets of test data. The soil conditions here is very similar to the Muar Flats test site where the Malaysian Highway Authority carried out the excellent program of test embankment with various type of novel ground improvement techniques. The most influencing factor in the design of the PVD system at this

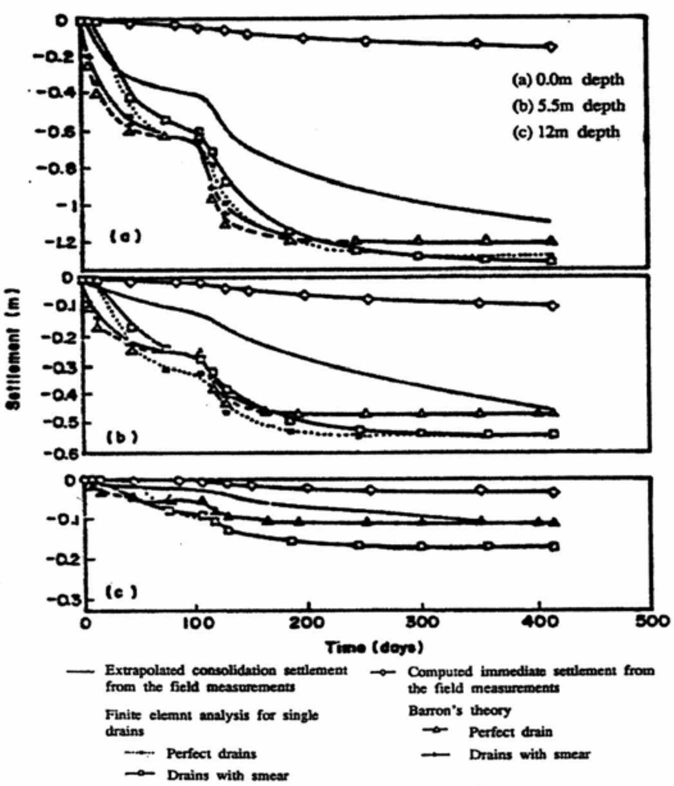


Figure 6: Computed and measured settlements of Muar test embankment with PVD.

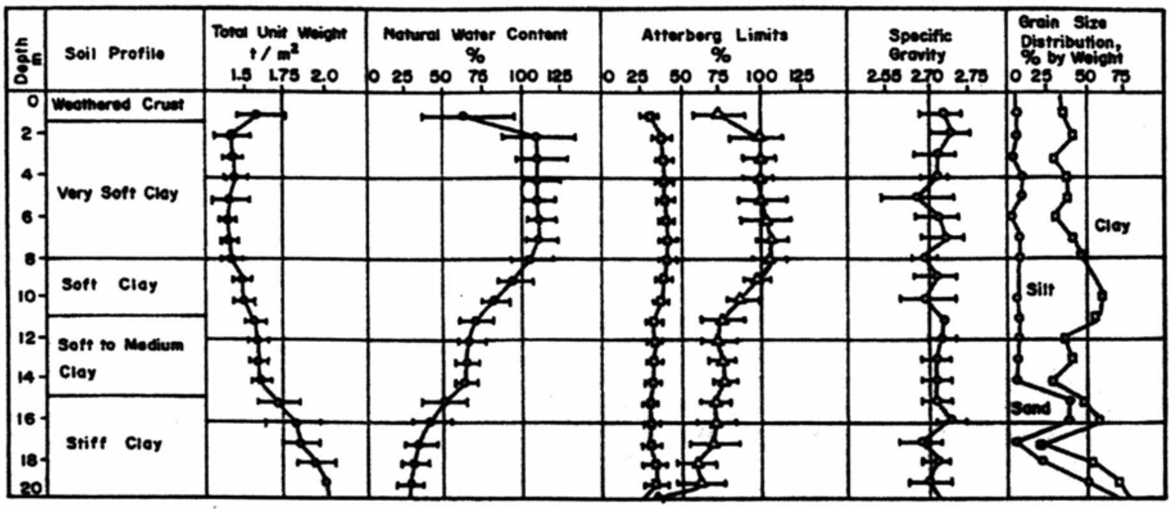


Figure 7a: Typical soil profile in the Bangkok plain

site and in other sites in Bangkok is the piezometric draw down which starts at a depth of 10 meters caused by excessive withdrawal of ground water. In the Bangkok plain such piezometric drawdown affects the design of piled foundations, excavations etc in addition to the ground improvement work with the use of PVD and surcharge loading. Novel interpretation techniques have to be used in estimating the excess pore pressures due to surcharge loading and the dissipation of excess pore pressures as the consolidation progresses. The piezometric draw down is shown in Fig. 7b. Three test embankments were constructed at the site for the evaluation of the performance of different type of PVD. The results from one test embankment labeled TS-3 will be presented here. The embankment base dimensions are 40m by 40m, maximum height 4.2m and side slopes 3:1; the surcharge corresponds to 75 kPa. The soil profile (as shown in Fig. 7) comprises 2m thick weathered crust overlying approximately 10m of very soft clay which is in turn underlain by a 4m thick medium stiff clay followed by alternating layers of stiff clay and dense sand. The

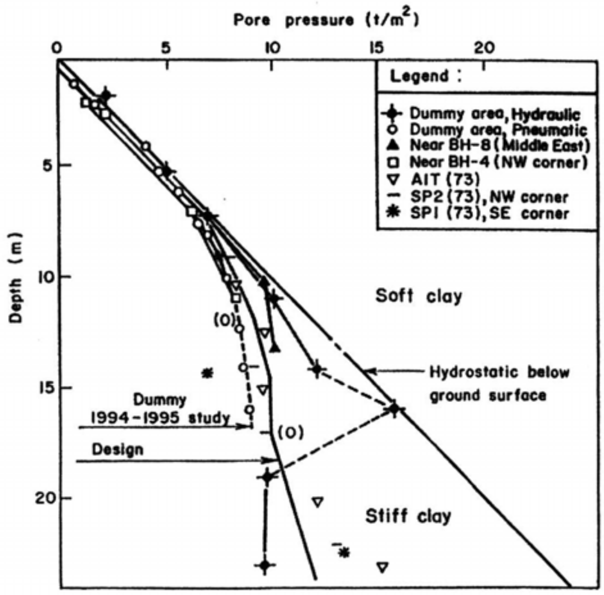


Figure 7b: Piezometric draw down at the Second Bangkok International Airport (SBIA) site

PVD was installed to a depth of 12m at spacing of 1.0 m in a square pattern. The piezometric level with depth is characterised by negative draw down at around 8 to 10 m depth caused by ground water pumping. The positions of the instruments installed are shown in Fig. 8. The settlement of the test embankment as well as the lateral movement of the sub-soil was measured with shallow and deep settlement gauges and slope indicator casings. Settlement computations were made from direct measurements and from pore pressure dissipation and degree of consolidation were computed by both methods to ensure that nearly 90 % of the settlement is due to consolidation and perhaps about 10 percent due to undrained movements. The increase in the undrained strength in the field was monitored with periodic vane tests and also compared to check its match with those computed from SHANSEP approach.

The measured settlement profiles and lateral movements are shown in Figs. 9 and 10. The computation from finite element analysis with coupled consolidation using critical state theories were also found to match the measured settlements, lateral movement, and pore pressure dissipation (as shown in Figs. 11 to 14). The total pore pressure measurements and their dissipation are shown in Fig. 15. These values are used in the computation of settlement due to pore pressure dissipation. The degree of consolidation from pore pressure measurement agrees with those computed from settlement measurements (see Fig. 16). Increase in field vane shear strength is illustrated in Fig. 17. Novel plots were made to estimate the secondary consolidation and the lateral movement due to creep (see Fig. 18). Also, the observations seem to indicate a reduction in ch values (see Fig. 19). The data from the Muar flat site also indicated a phenomenon similar to well resistance in the drains. Indraratne have done some good work on the smear effects to explain such phenomenon, while Hansbo worked on non-Darcian flow theory. The progressive increase in the lateral movement with time during high surcharge still needs to be modeled using undrained creep theories. This case history indicates the success of the use of consolidation theories and critical state concepts in coupled analysis using finite element methods.

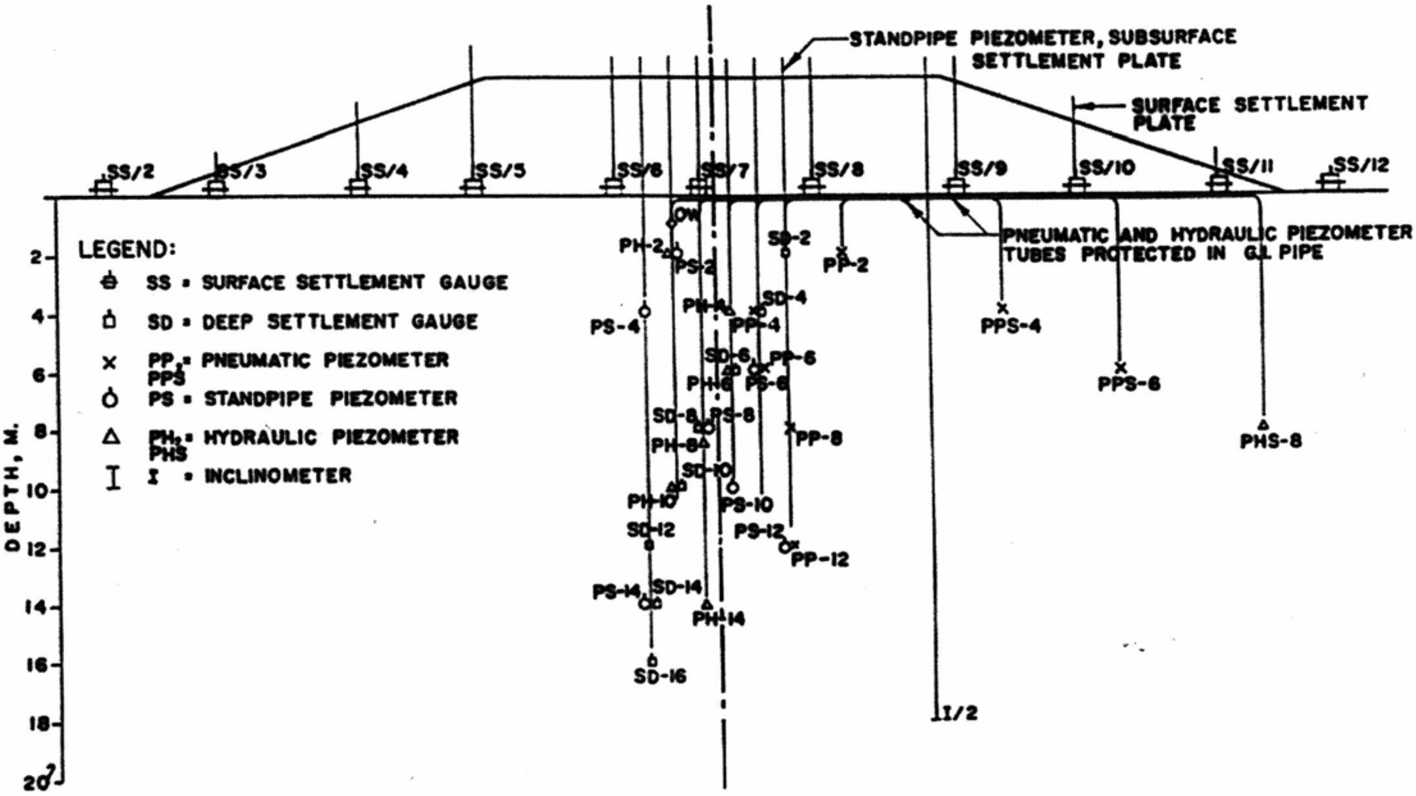


Figure 8: Section view of the test embankment showing the position of instruments at the Second Bangkok International Airport (SBIA)

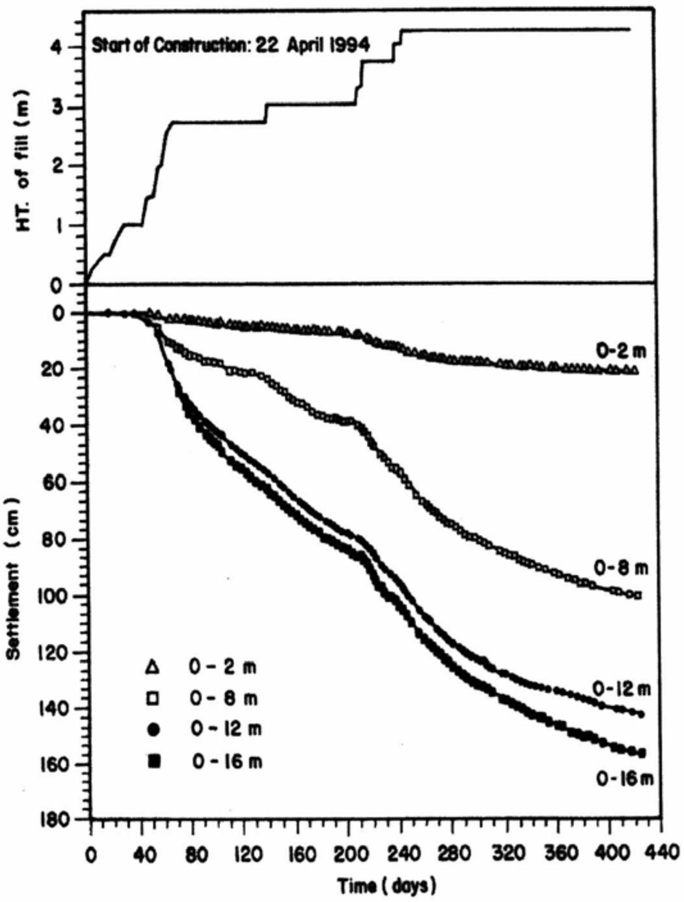


Figure 9: Settlement-time plot of the embankment with PVD at the SBIA site in Bangkok

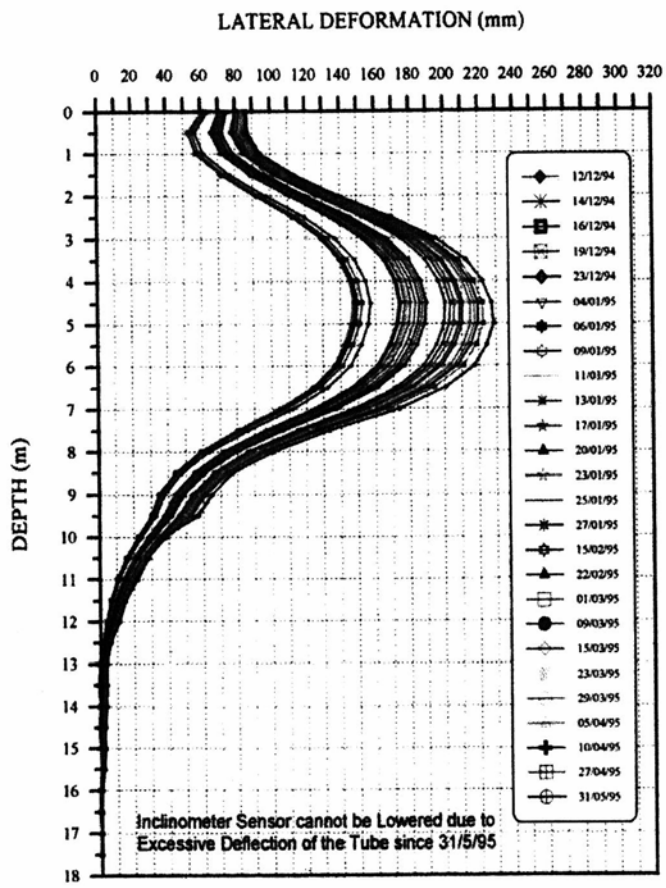


Figure 10: Lateral deformation with depth below embankment TS3 at the SBIA site in Bangkok

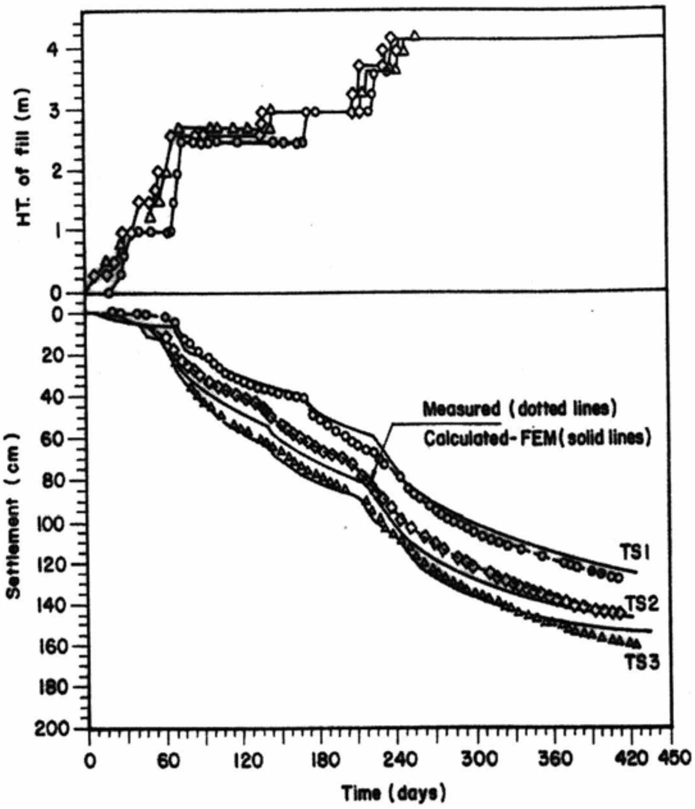


Figure 11: Measured and computed settlement for the test embankment with PVD at the SBIA site in Bangkok

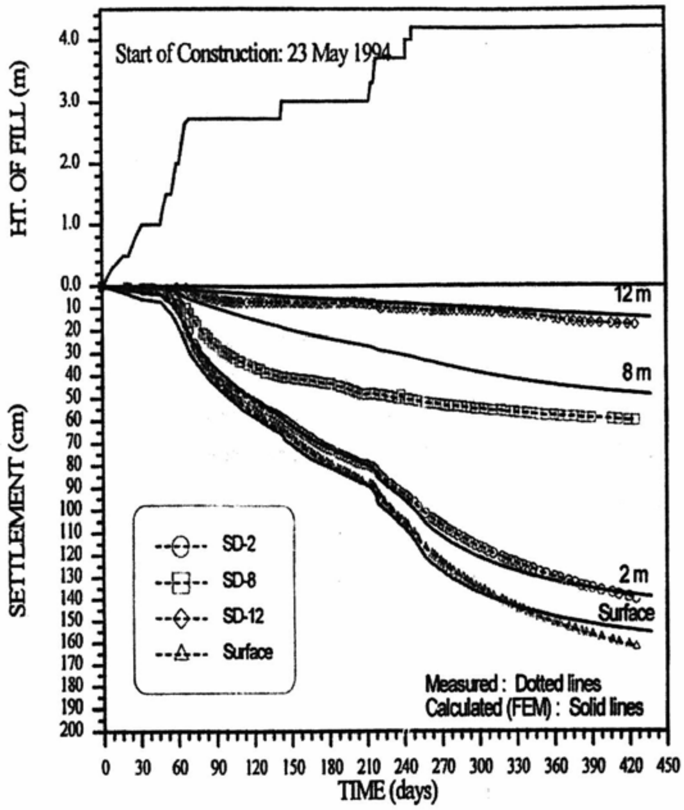


Figure 12: Measured and computed settlement with different depth at the SBIA site in Bangkok

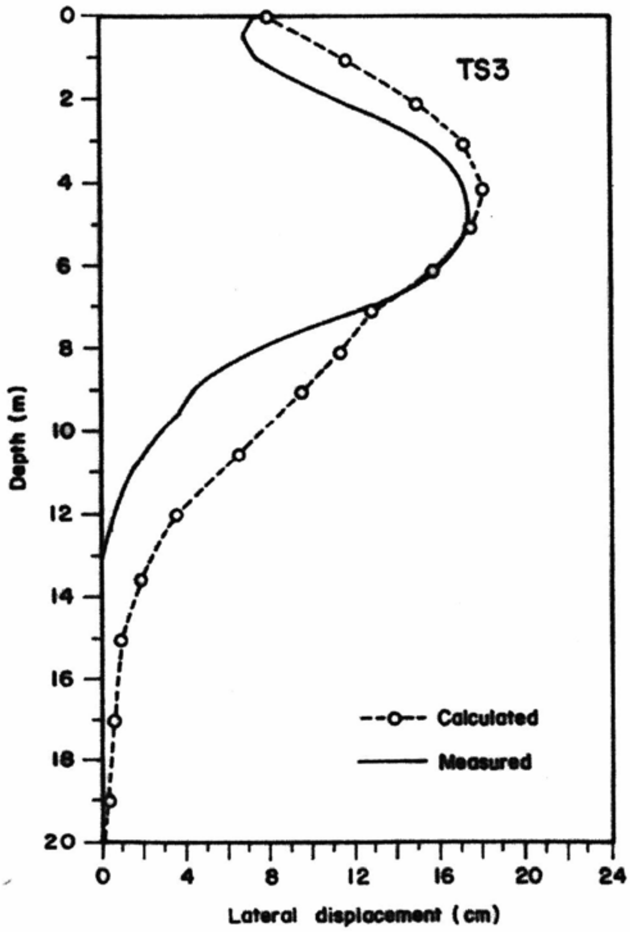


Figure 13: Measured and computed lateral movement of the embankment at the SBIA site in Bangkok

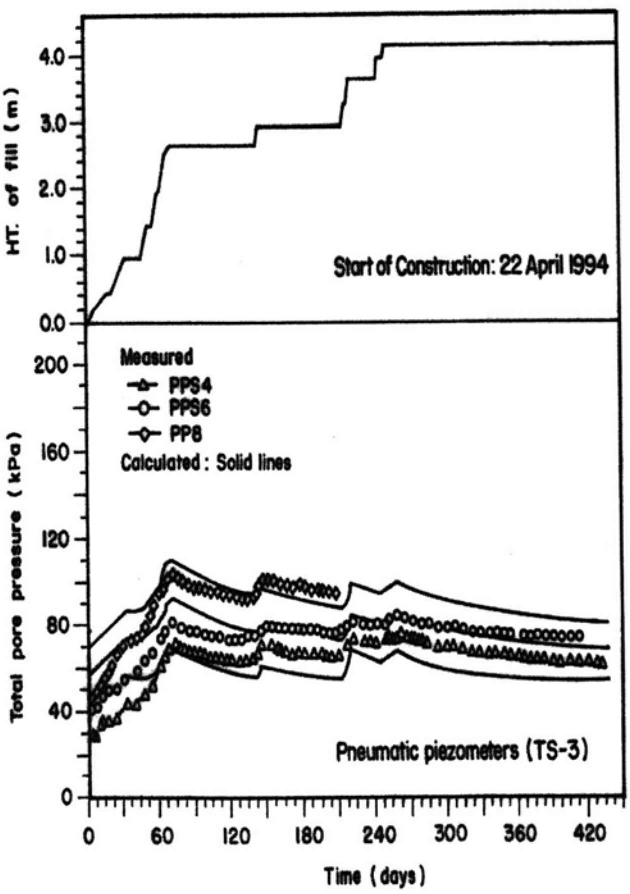


Figure 14: Measured and computed pore pressure dissipation of the embankment at the SBIA site in Bangkok

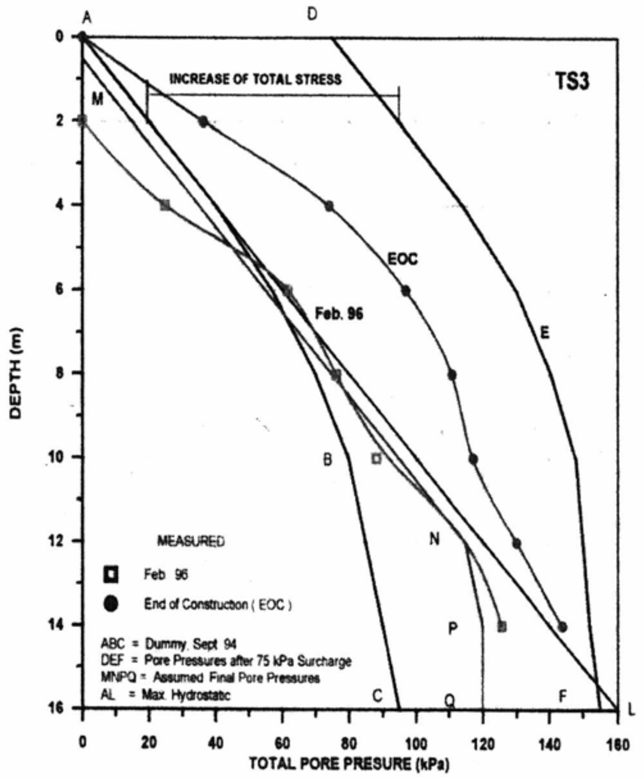


Figure 15: Pore pressure distribution with depth at various time intervals at the SBIA site in Bangkok

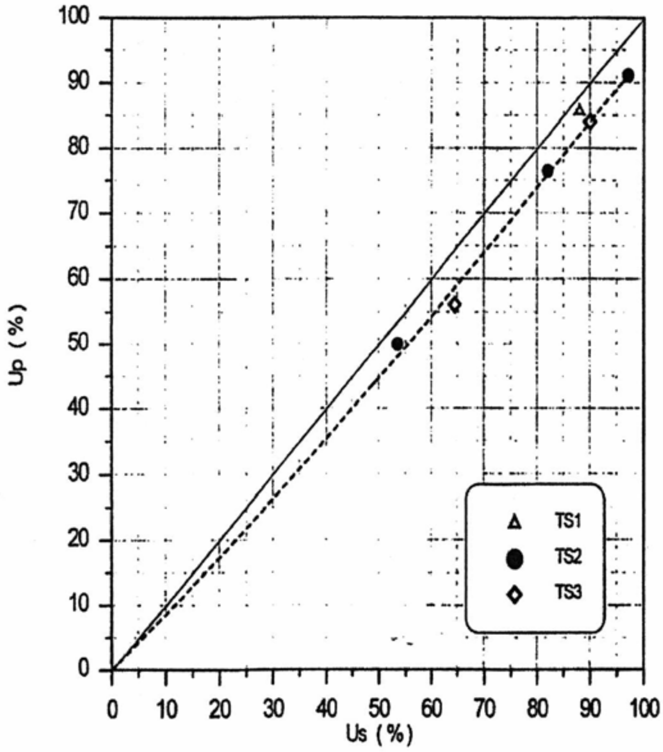


Figure 16: Comparison of the degree of consolidation from pore pressure dissipation and from settlement measurements

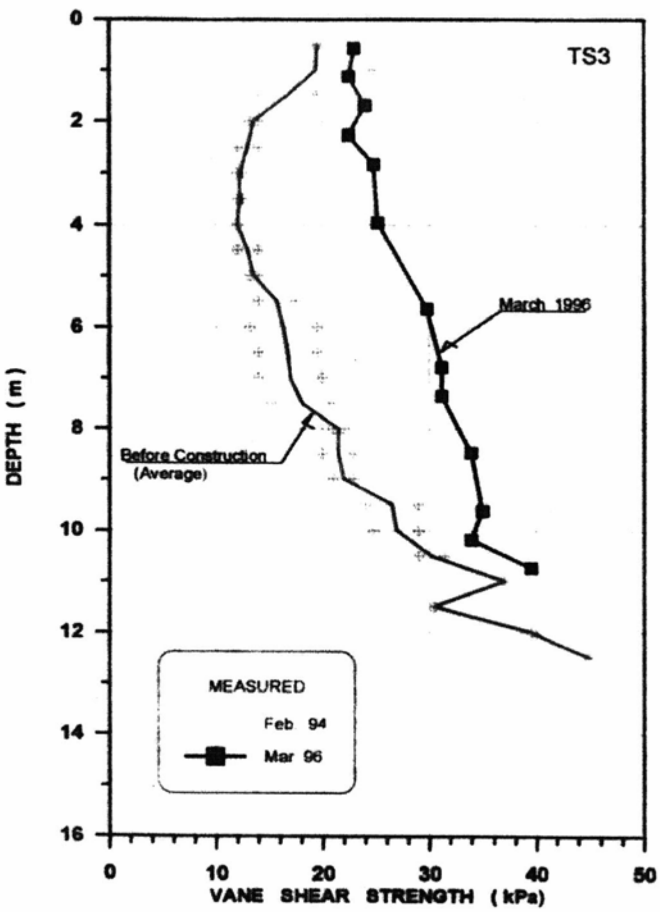


Figure 17: Improvement in field vane shear strength with consolidation settlement due to surcharge with PVD at the SBIA site in Bangkok

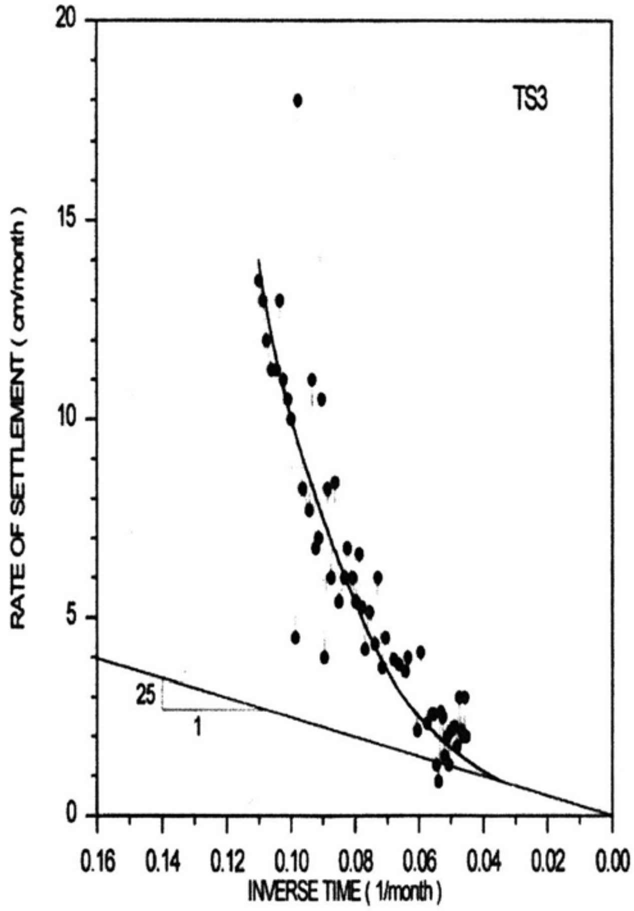


Figure 18a: Reduction of the settlement rate with time for the PVD embankment at the SBIA site in Bangkok

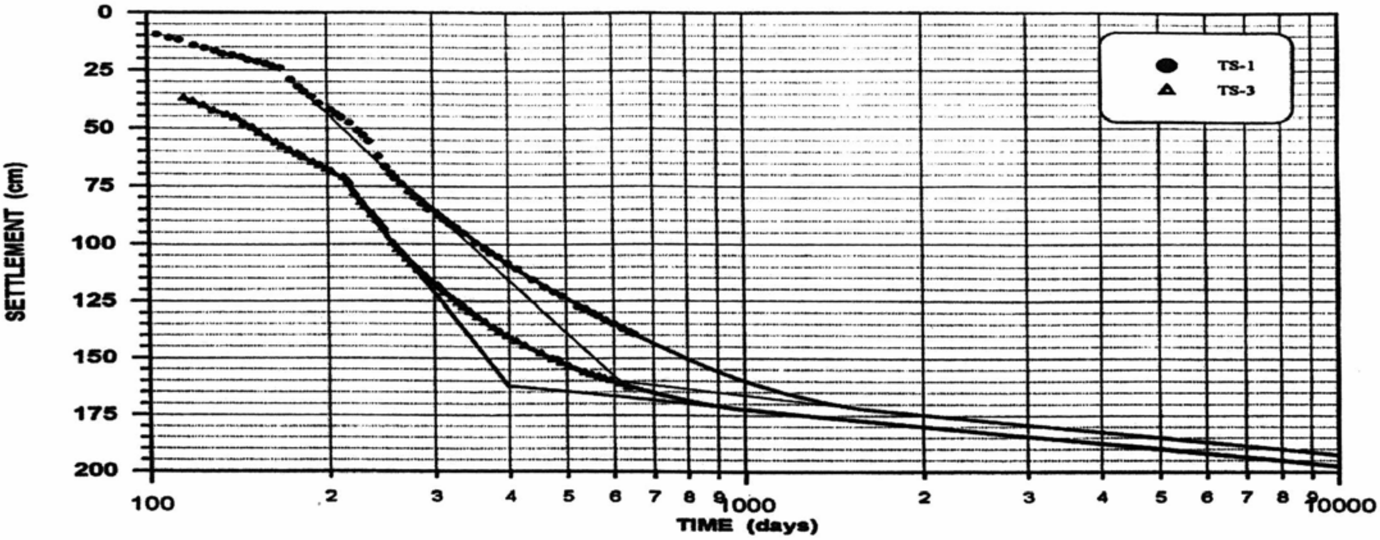


Figure 18b: Settlement versus log-time plot for two test embankment at the SBIA site in Bangkok

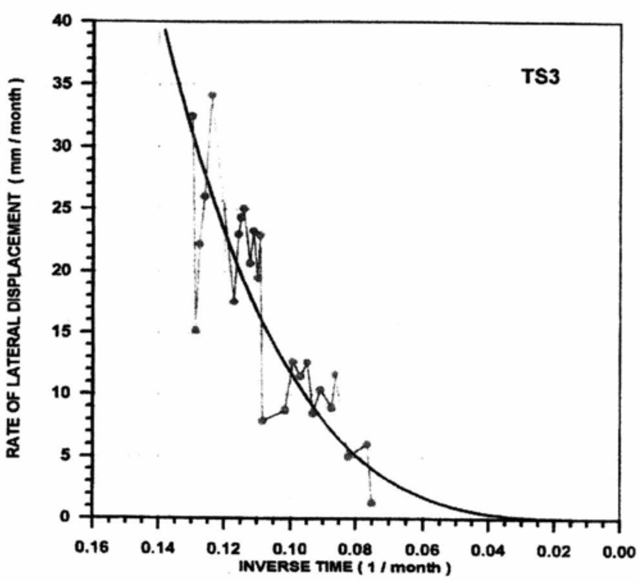


Figure 18c: Reduction in the rate of lateral movement with time at the SBIA site

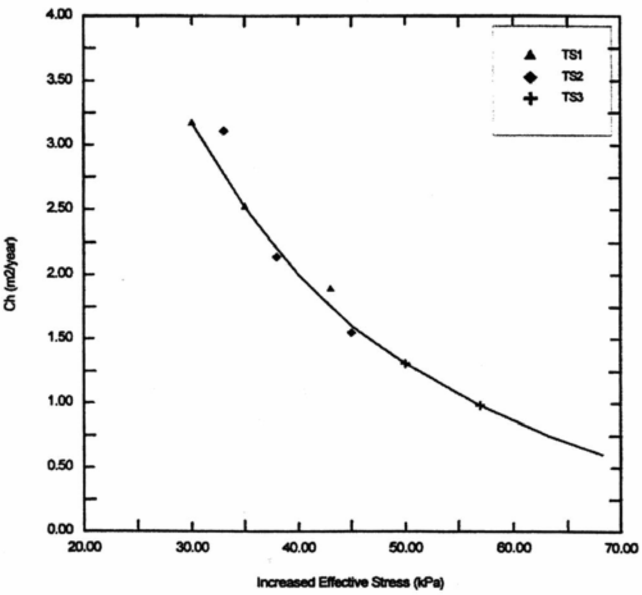


Figure 19: Back calculated c_h values from the settlement measured at the SBIA site test embankment

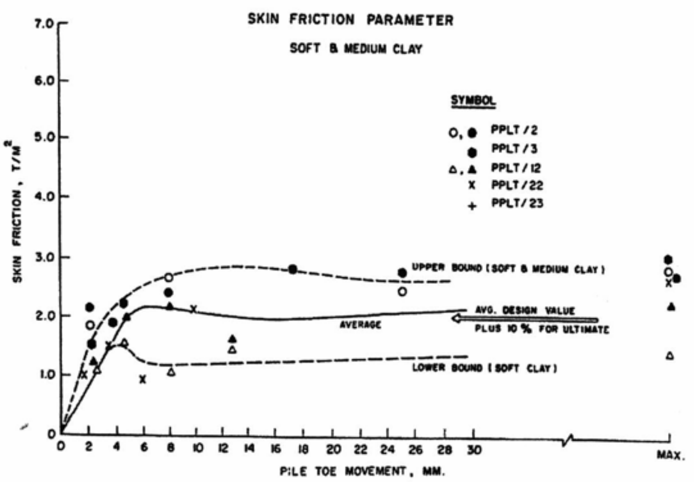


Figure 20: Development of skin friction for bored pile in soft clay in the Bangkok plain

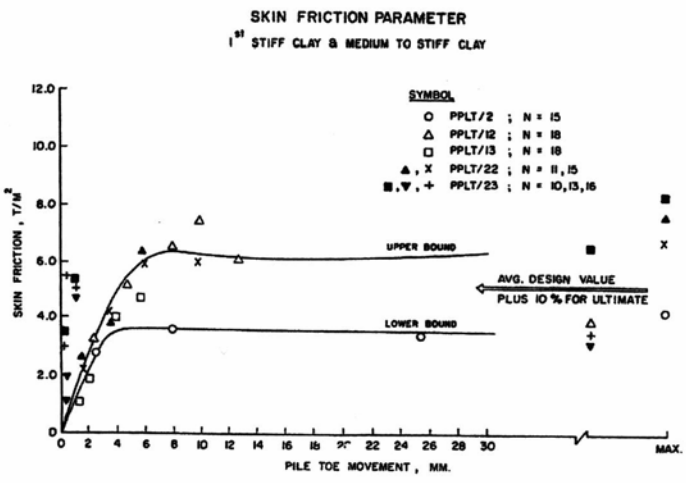


Figure 21: Development of skin friction for bored pile in medium stiff clay in the Bangkok plain

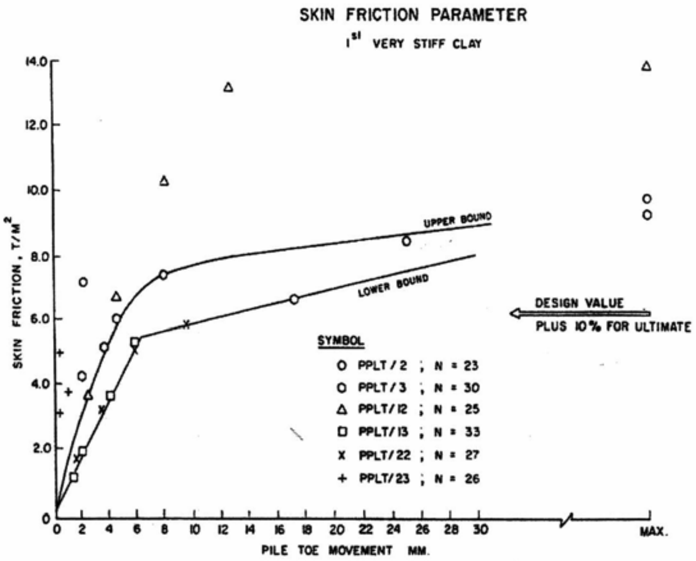


Figure 22: Development of skin friction for bored pile in stiff clay in the Bangkok plain

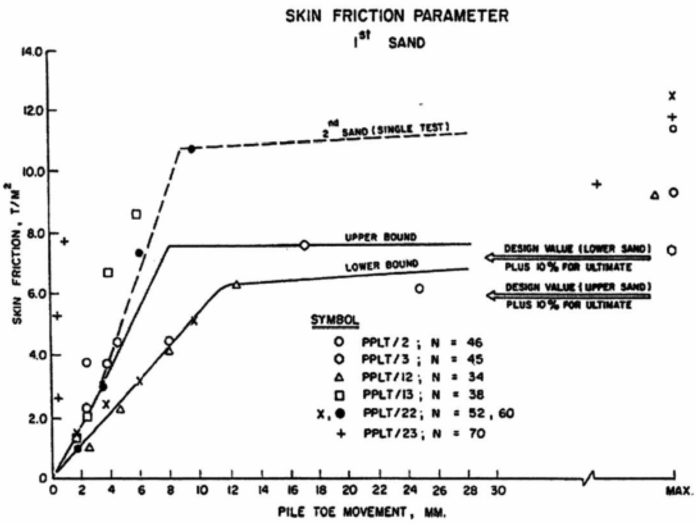


Figure 23: Development of skin friction for bored pile in sand in the Bangkok plain

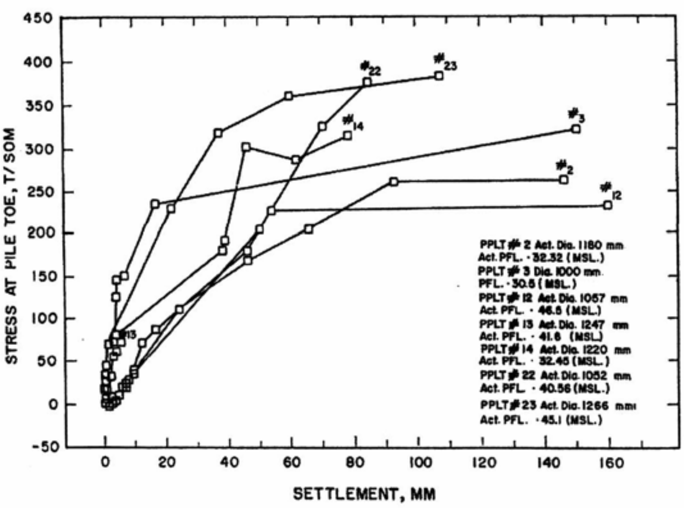


Figure 24: Stress versus settlement of strain gage

PILED FOUNDATIONS IN THE BANGKOK PLAIN

In the early days, driven piles were used in Bangkok up to the first sand layer, as these piles are easy to drive through soft clay and stiff clay. With the introduction of bored piles large capacity of load can be carried, with piles of the order of 1.0 to 2.0 m in diameter, some time extending to as deep as 50 to 55 m in the second sand layer. It is often found that the bored piles carry little load in end bearing even at the ultimate load close to failure. The load transfer measurements carried out in the Second stage expressway indicate the development of skin friction with movement in the soft clay, medium stiff clay, and stiff clay and in sand; these data are presented in Figs. 20 to 23. Also, the mobilization of end bearing is shown in Fig. 24. These data are useful in establishing how the adhesion values and friction values in clays and sand develop with the deformation pattern and can be used to establish a deformation based load capacity in piles, rather than an ultimate load capacity used with a factor of safety to establish the working load. Such data can also be used to establish design procedure for piled raft foundations.

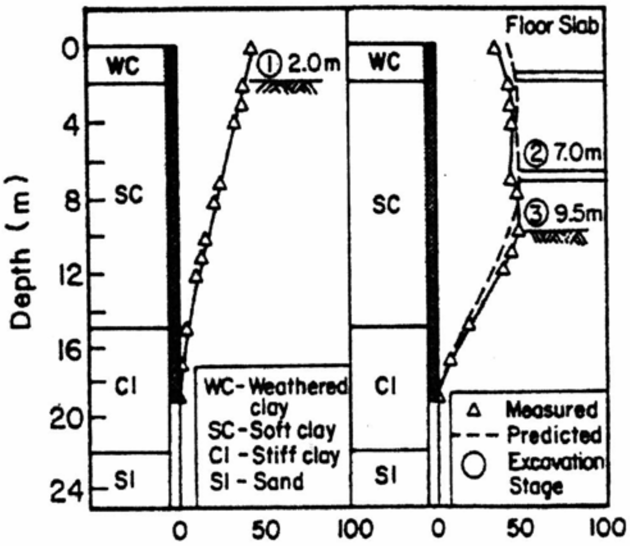


Figure 25a: Site A

SMALL STRAIN CASE STUDIES - EXCAVATIONS

In this section the deformation analysis of deep excavations in the Bangkok sub-soil is presented for four sites labeled A to D. In site A, the excavation was 9.8 m deep with three level basements. The excavation was supported by 0.82 m thick diaphragm wall up to 17m depths. The barrette legs were installed at the bottom of the wall to a depth of 44 m with a horizontal spacing of 5.4 m. Top-down construction method was adopted and two floor slabs were constructed at depths of 2.0 m and 7.0 m, which functioned as bracing during excavation (see Fig. 25a).

In site B (see Fig. 25b), the excavation depth was 15.5 m for four level basements. This excavation was also supported by diaphragm wall of 0.82 m thickness with the end bearing at 20 m. Three floor slabs formed as internal bracing at 0.0, 2.0 and 9.5 m depths, which were formed by top-down method.

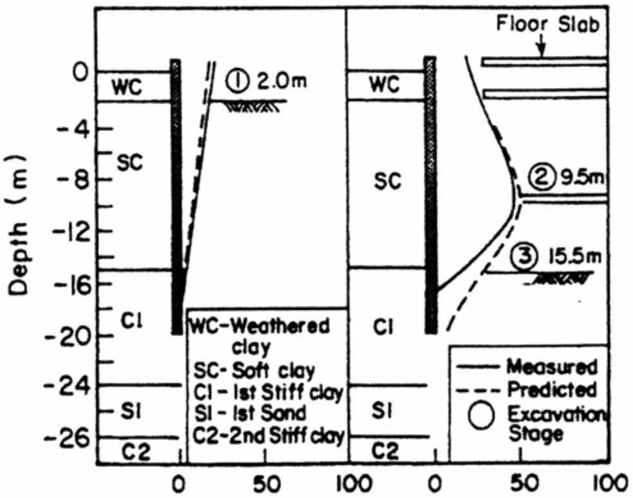


Figure 25b: Site B

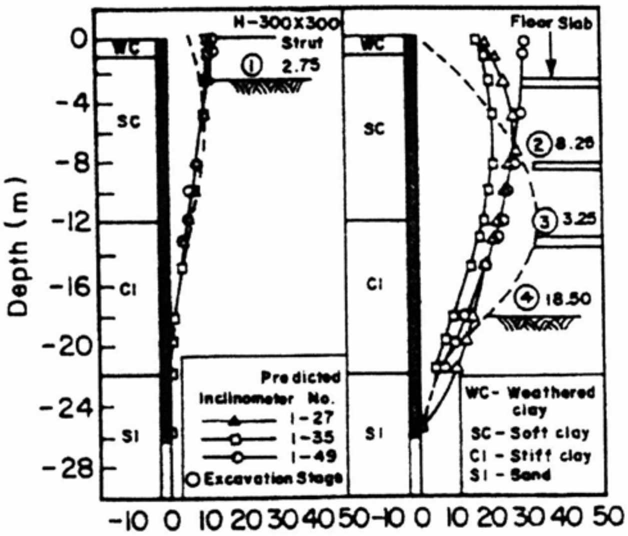


Figure 25c: Site C

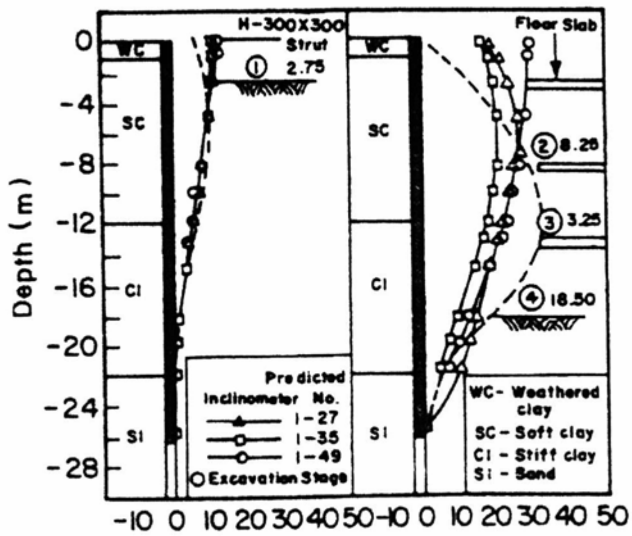


Figure 25d: Site D

Figure 25: Computed and measured lateral movement of excavation with diaphragm walls in the Bangkok Plain

In site C a 26.0 m deep, 0.82 m thick diaphragm wall was used to support an excavation of 18.5 m depth. Barrette piles were installed below the wall to a depth of 50.0 m. Three concrete slabs were constructed by top-down method as supporting systems at 2.75, 8.25 and 13.25 m depths (refer Fig. 25c).

In site D, a 1.0 m thick and 20.0 m deep diaphragm wall was used to support a 16.0 m deep excavation. The bracing system consisted of strut-wales and king posts. The struts were pre-loaded as well (see Fig. 25d).

The soil parameters used with the CRISP program in the embankment studies in the Bangkok Plain and in the Muar Flat site in Malaysia are given in Tables 1 to 4.

Table 1: Soil parameters used for FEM analysis of PVD improved embankment with surcharge in the Bangkok Plain

DEPTH (m)	κ	λ	M
0 - 2	0.07	0.34	1.20
2 - 7	0.18	0.90	0.90
7 - 12	0.10	0.50	1.00
12 - 15	0.07	0.34	1.20
15 - 18	0.02	0.10	1.20

Table 2: Soil parameters used for FEM analysis of PVD improved ground with vacuum preloading in the Bangkok Plain.

DEPTH (m)	κ	λ	M
0 - 1	0.03	0.30	1.20
1 - 8.5	0.08	0.73	1.00
8.5 - 10.5	0.05	0.50	1.20
10.5 - 13	0.03	0.30	1.40
13 - 18	0.01	0.10	1.40

Table 3: Soil parameters used for embankment in study Muar clay

DEPTH (m)	κ	λ	M
0 - 2	0.06	0.16	1.19
2 - 6	0.06	0.16	1.19
6 - 8	0.05	0.15	1.12
8 - 18	0.04	0.09	1.07

Table 4: Soil parameters used for the analysing reinforced embankment in Muar clay

DEPTH (m)	κ	λ	M
0 - 2	0.06	0.35	1.20
2 - 7	0.10	0.61	1.07
7 - 12	0.06	0.28	1.07
12 - 18	0.04	0.22	1.07
18 - 22	0.03	0.10	1.20

The corresponding values used in the excavations are given in Table 5. These soil parameters are somewhat different from those used in the embankment studies. Especially, the I values are now different and too low for the excavation when compared to the embankments. The critical state theories are deficient in modelling the undrained stress strain behaviour and also these theories are developed for normally consolidated clays, while all natural deposits such as the soft Bangkok clay are lightly over-consolidated. A stress strain theory of the Pender type developed for over-consolidated clay is more appropriate to model the undrained stress strain behaviour of lightly over- consolidated clays.

An additional feature to be remembered in small strain excavation problems is that the stress conditions are far below the failure states. Therefore pressure diagrams of the type, which have their origin to active and passive stages, are never realised, as these limiting stages are never reached at such small strains. Also, the modelling of adhesion on the soil-wall contact and the effect of already installed piles on the excavation side need to be properly modeled based on the small strain deformation and not those based on failure states.

Table 5: Soil parameters used for the analysing of deep excavations in the Bangkok Plain

DEPTH (m)	κ	λ	M
0-2	0.053	0.182	1.05
2-15	0.090	0.358	0.93
15-22	0.026	0.111	0.88

GEOTECHNICS IN DEVELOPING COUNTRIES

The traditional Geotechnical Engineering works will continue to be in demand in the developing countries. Most of these projects are on terrains which are somewhat different from those on which the classical soil mechanics is developed. Thus there is a strong need for us in the developing countries to concentrate more on the laboratory and field behaviour of soils in the tropical climates. It seems nowadays there is a feeling that the use of various types of computer softwares will solve all our problems and there is no need to concentrate anymore on soil testing. Even though the economic downturn has hindered the development and applications of Geotechnics, the future of the subject is more relevant and needed in the developing countries where the infrastructure developments are still a necessity. Developing countries must have their own journals to publish papers which are of regional importance and in this sense the contributions from the Southeast Asian Geotechnical Society over the last 35 years of its life is enormous and we must continue to support the activities. The late Tan Sri Prof. Chin is the second President of the Society following, Dr. Za- Chieh Moh and was very active in the Society from the date of its formation until his death in 1991.

CONCLUSIONS

This Tan Sri Professor Chin Lecture is given to illustrate the importance of the development of Geotechnics in developing countries. A new type of approach and emphasis be made to educate engineers in each country to be familiar with the soil conditions, which is experienced predominantly in their region. When this is combined with the classical soil mechanics in an intelligent manner, better quality graduates can be produced. Case histories are presented from Malaysia and Thailand in which small scale and large scale tests were performed for a better analysis of the major projects. A continuous need to study the regional soils and to well document them in the Southeast Asian Journals is also emphasised. A cautious approach to the use of various computer softwares in relation to the type of strain level in which the analysis need to be performed is also illustrated.

ACKNOWLEDGEMENTS

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(no references for this article)