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**BACK ANALYSIS OF SUBSIDENCE DUE TO
FILLING AND GROUND WATER LOWERING**

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BACK ANALYSIS OF SUBSIDENCE DUE TO FILLING AND GROUNDWATER LOWERING

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ABSTRACT:

The study illustrates how simplest analytical procedures are capable of analyzing complicated problems. The site studied was newly reclaimed and consolidation is still ongoing. The groundwater table at the site was once much lowered for the construction of three underground tanks. Ground settlements have been continuously monitored since mid-1986. Analyses were performed using the simplest analytical procedures to compute consolidation settlements caused by the adding of the fill and the lowering of the groundwater table, and the results obtained are in an excellent agreement with the readings. The lesson learned: construction details have to be properly included into consideration for analyses to be meaningful.

INTRODUCTION

According to a report by Water Resources Planning Commission (WRPC) of Taiwan, there are 200,000 pumping wells in operation on the island drawing 7.3 billion tons of water from the ground annually, of which 44% is utilized for irrigation, 33% for fish farming, and the remaining 23% for industrial and domestic use. As a result, as shown in Fig. 1, a total of 1,170 sq.km of land has experienced ground subsidences varying from 0.5m to 2.5m. This equals to 11% of the plain on the island. The problem has become so serious that some of these areas are now below the sea level and are relying on levees for protection. Concerning about the consequences, the central government initiated a pilot study in 1992 for the purpose of establishing procedures for an island-wide evaluation of the situation with the goal of deciding public policies regarding groundwater control. The study does not intend to come up with new theories, rather, it only attempts to identify procedures which, preferably as simple and as practical as possible, are capable of correlating theories with observations.

THE SITE AND THE GROUND CONDITIONS

The site chosen for the study is a piece of land now being used for storing liquefied natural gas, as depicted in Fig. 1, located only a few kilometers to the south of Tainan City. Although locally ground settlements have exceeded 2m due to construction activities, it is not in a region in which ground subsidence is the most serious. It was chosen for the reasons that: (a) the site has been fully explored and the ground conditions are well documented, (b) the groundwater

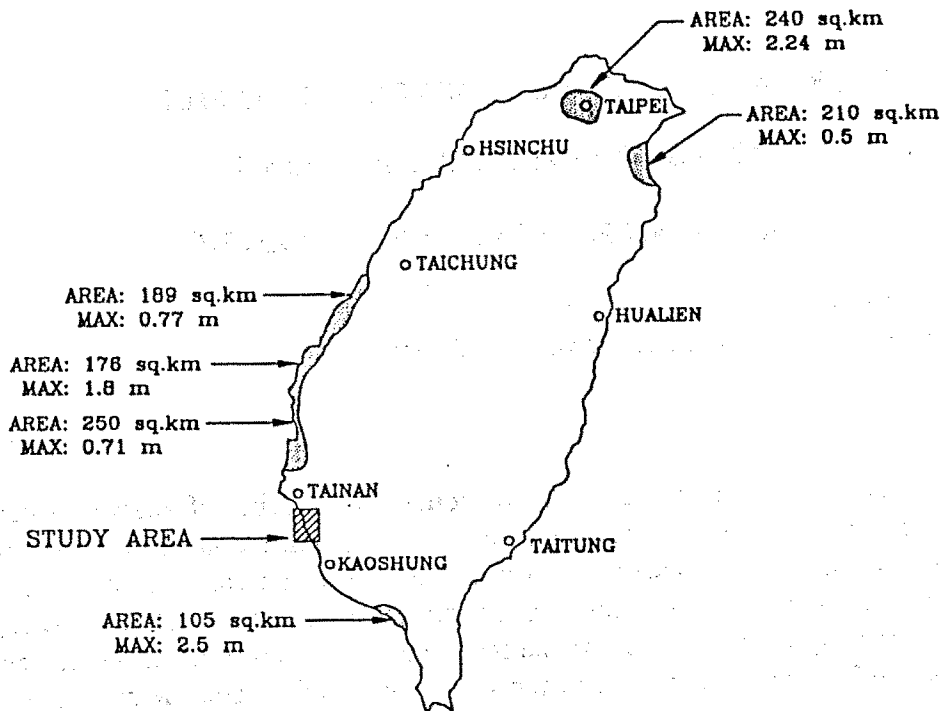


Fig. 1 Areas in Which Settlements Exceed 0.5m

table has been continuously monitored, and most importantly, (c) long-term settlement readings are available.

Reclamation started in 1985 by using sands dredged from seabed and took four and a half years to complete. The water depths varied from 3 to 9m before filling (see Fig. 2) and the final ground surface is about 3.6m above the mean sea level. A typical profile, obtained at E-1, see Fig. 2 for location, is given in Fig. 3. In short, the fill is underlain, to a depth of 50m or so, by an alternation of fine sand and clay layers with SPT blow counts, in general, varying from 20 to 40. Between depths of 50m to 100m, the soils are predominantly silts and silty clays.

INSTRUMENTATION AND MONITORING

Numerous instruments have been installed at the site and their locations are shown in Fig. 2 (not exhaustively). They fall into the following categories:

- a) Ground water table - piezometers (HP) and observation wells (OW)
- b) Surface settlements - settlement points (SP), settlement rods (SR)
- c) Settlements at depths - borehole extensometers (E - rod type), continuous settlement gages (SG - magnetic ring type)

Settlement rods are steel rods which are connected to plates placed on ground surface and can be extended as fill is placed.

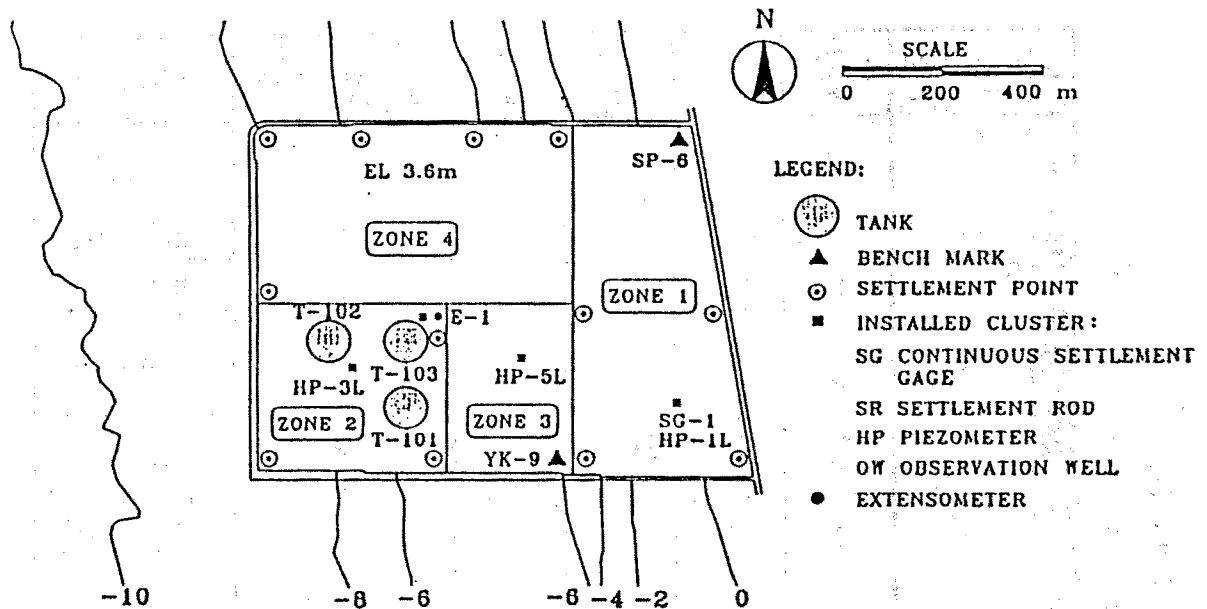


Fig. 2 Site Plan

Levels were taken by using a Wild NA3000 Electronic Level which gave errors of closure, from experience, usually within 1.5mm for loops of 500m in total length. The positions (x, y and z) of survey points were also determined by using the Global Positioning System (GPS) which is an advanced technology for survey in very large areas. It, as illustrated in Fig. 4, receives signals from satellites orbiting around the Earth and by differentiating the distances between the station and these satellites, the absolute position of the station can be determined. The accuracy in measurements depends on the number and the positions of the satellites and the ability of software in eliminating errors. An area extending 2 km to the west and 3 km to the north of the site was surveyed to test the accuracy of the system and to see if the system can be used for monitoring the subsidence along the entire coast. The maximum error, in comparison with the results obtained by using the WILD NA3000 is about 40mm, and is not related to the distance to the bench mark. This value is sufficiently small for the system to be adopted for areas with rates of settlement of, say, twice as much. Efforts are being made to improve the accuracy of the system and it is quite promising that the accuracy can be further improved.

ANALYTICAL MODELS

Ground settlements, in general, are a result of consolidation which is a process for excess pore water pressure to dissipate leading to reduction in void ratio and, hence, the volume of soil mass. In the case studied, excess pore water pressures came from two sources: increases in the overburden pressures as a result of filling, and lowering of groundwater table as a result of pumping. Both have to be accurately incorporated in the analyses for the results to be right.

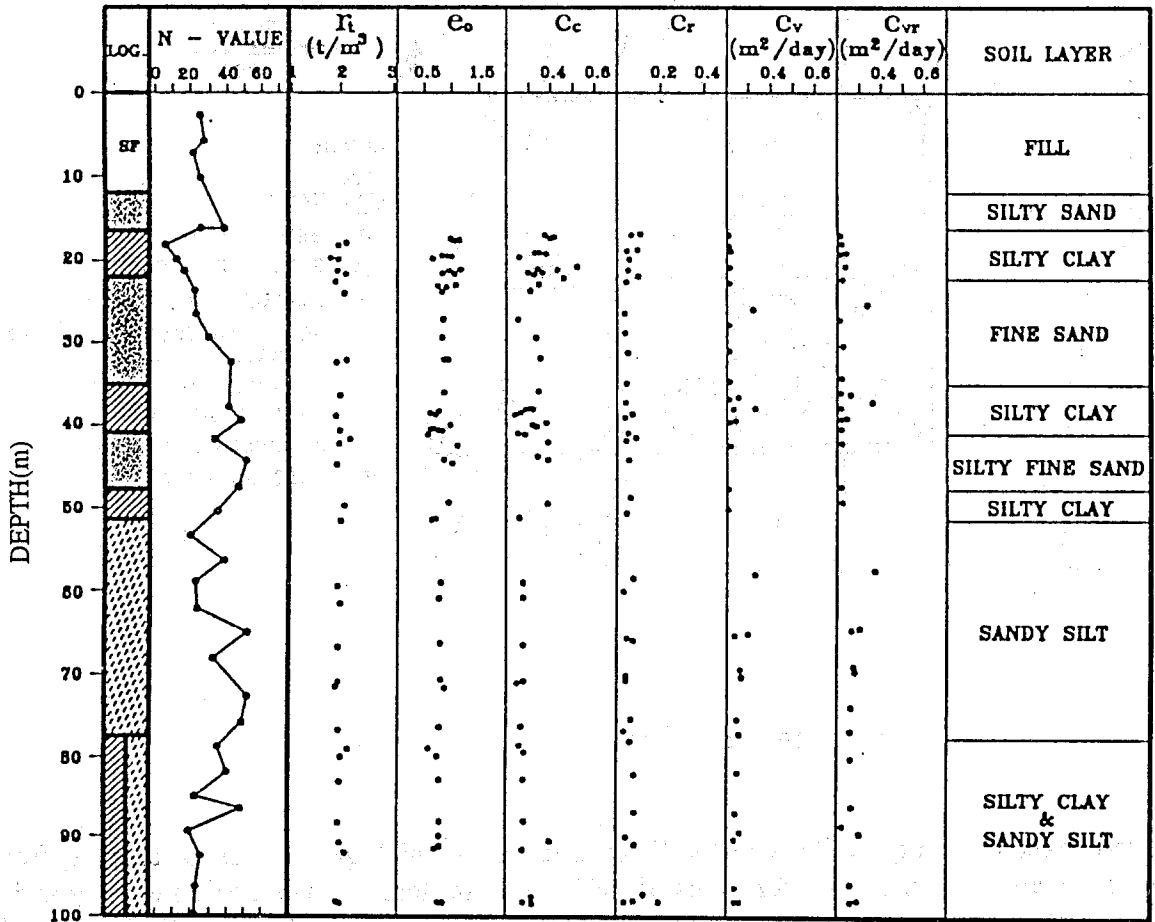


Fig. 3 Typical Soil Profile And Soil Parameters at the Site

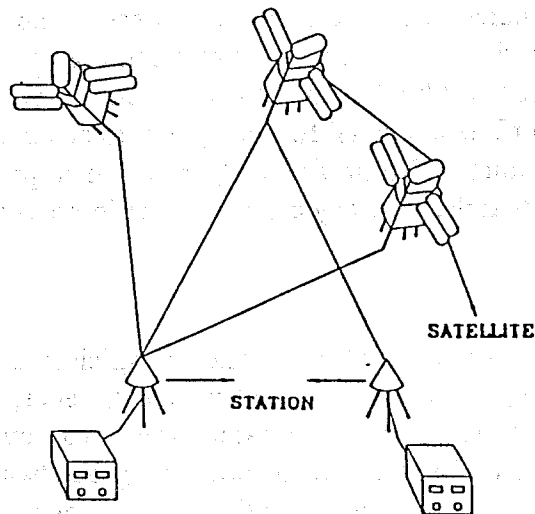


Fig. 4 Principle of Global Positioning System

Of many locations at which settlements have been monitored, SG-1 and E-1 were selected for back analyses. At SG-1, settlements were monitored by using a continuous settlement gauge with magnetic rings mounted on a flexible plastic tube at various depths. These rings moved together with the surrounding soils as soils settled. Their positions were detected by a sensor which triggered an electrical current upon entering the magnetic field of a ring. At E-1, settlements were measured by an extensometer which contains rods anchored at various depths. By measuring the changes in elevation at the top of each rod, the settlements at the bottom were determined.

Effects of Filling

As shown in Fig. 2, the site is divided into four zones and the schedule of filling is as follows:

Zone 1	Jan	85	-	May	85
Zone 2	Oct	85	-	Mar	86
Zone 3	Mar	87	-	May	87
Zone 4	Apr	88	-	May	88

The maximum thickness of the fill is about 13m. The increases in the overburden pressures due to the weight of fill were computed by using the Boussinesq equations (Boussinesq, 1885) which are classical solution for stresses in elastic media. Since the procedure is available in numerous textbooks, no details will be given herein.

At Location SG-1, since filling was completed in a relatively short period and was completed long before the monitoring of settlements started, the fill can be assumed to be placed in one step. Furthermore, because Zone 1 covers a very large area, the stress increments can be assumed to be constant along the entire depth of interest. At Location E-1 which is at the junction of Zones 2, 3 and 4, it is, however, necessary to compute the stress increments due to filling in different zones separately and the results are given in Fig. 5. Since consolidation is a time-dependent process, not only the sequence but also the timing of each stage of filling must be properly accounted for.

Groundwater

The three underground tanks, 70m in diameter, were constructed in the 1987 and 1988. Diaphragm walls with a thickness of 1.5m were installed to a depth of 90m and excavation reached a depth of 44m below surface.

Pumping was carried out both inside and outside the pits during construction to enable excavation to proceed. Within the upper layers, there are three piezometers, namely, HP-1L, -3L and -5L, available and their locations are shown in Fig. 2. The readings are plotted in Fig. 6 and, as can be noted, that the maximum drawdowns exceeded 18m. Since the number of piezometers is limited, it is necessary to estimate the drawdowns at other places, for example, E-1, based on the available information.

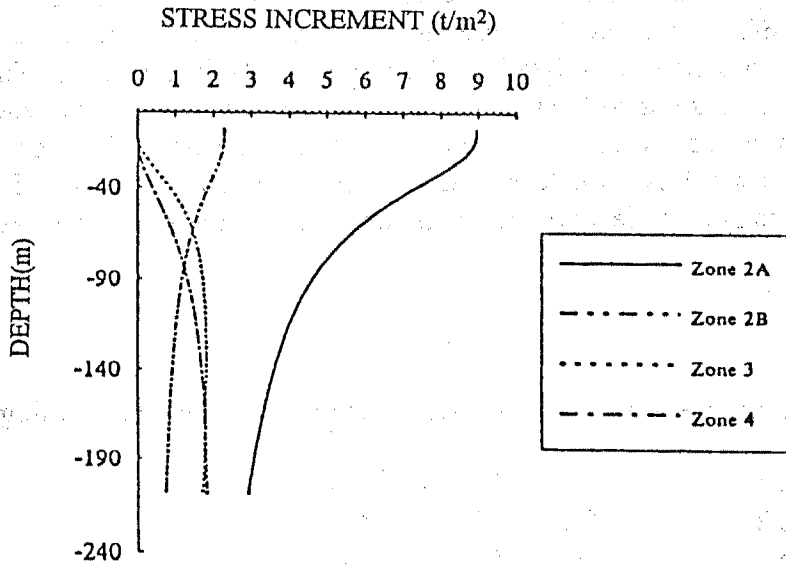


Fig. 5 Stress Increments at E-1 Due to Filling in Different Zones

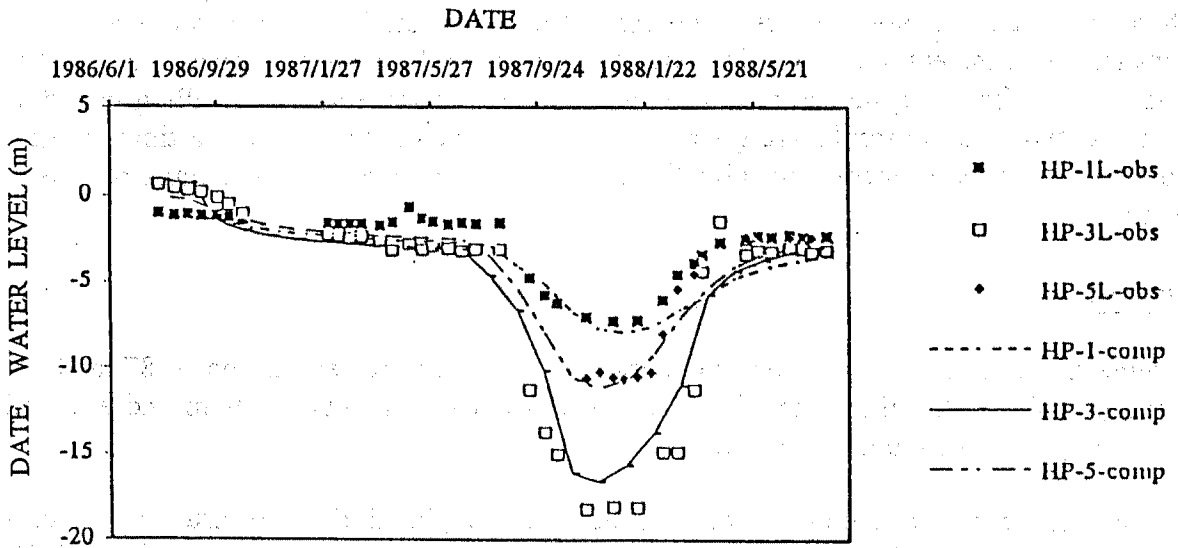


Fig. 6 Observed and Computed Water Drawdowns

Since (a) the subsoils are not uniform with layers of sand and clay, and (b) there were several pumps surrounding each pit, theoretically, this is a 3-D non-linear problem requiring sophisticated finite element analyses. However, beyond a distance of, say, 20m or so away from the perimeter of excavation, each tank can be pretended to be a single well for the purpose of computing drawdowns. Furthermore, the following assumptions are made:

- (a) the interaction effects among tanks are negligible, and
- (b) the seepage involves only horizontal flows

The problem then can be simplified to conventional 1-D linear analysis of which solutions are available in textbooks. Since drawdowns are time-dependent, the Theis non-equilibrium equations (Fletcher, 1986) shown below are appropriate:

$$s = \frac{Q}{4pT} w(u) \quad \text{Eq. 1}$$

$$w(u) = -0.5772 - \ln(u) + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + \dots \quad \text{Eq. 2}$$

$$u = \frac{r^2 S}{4Tt} \quad \text{Eq. 3}$$

where

- s = drawdown
- Q = pumping rate
- t = time
- T = transmissibility
- S = storativity
- r = distance from the center of well

For multiply wells, the total drawdown at any point can be obtained by superposition of the effects of all the wells.

According to records, pumping was carried out in the following periods:

Tank T-101	Jul 26, 87	-	Feb 3, 88
Tank T-102	Oct 20, 87	-	Mar 22, 88
Tank T-103	Sep 21, 87	-	Feb 21, 88

Other than the above information, nothing is available. Therefore, computations were performed by playing with the three parameters, ie. Q(t), S and T in an attempt to match the

observed drawdowns. The combination of $S = 0.4$ and $T = 4000 \text{ m}^2/\text{day}$ gives reasonable results and, as can be noted from Fig. 6, the results obtained are in an excellent agreement with the drawdowns recorded by piezometers. The calculation shows that, at the peak time the flow rate could be as much as 200,000 t/day.

Consolidation

The governing equation (Terzaghi, 1925) for primary consolidation, in its simplest form, is:

$$\frac{\partial u}{\partial t} = c_v \frac{\partial^2 u}{\partial z^2} \quad \text{Eq. 4}$$

where

u	=	excess pore water pressure
c_v	=	coefficient of consolidation
z	=	depth

This is the classical Terzaghi's theory of consolidation. Again, since solutions can be found in many textbooks, no further details will be given herein.

In addition to coefficient of consolidation, the soil parameters required include unit weight (γ), compression index (C_c) and initial void ratio (e_0) of soils. All these parameters were directly deduced from laboratory test results, are given in Fig. 3, and representative mean values were adopted in the analyses.

SETTLEMENT COMPUTATIONS

Computation indicated that the settlement of soils below the depth of 200m was practically nil, therefore, analyses were only performed for soils above a depth of 200m. As mentioned previously, extensometers are available at E-1 and SG-1 for monitoring settlements at various depths. The computed settlements at surface and at a depth of 50m are compared with the readings obtained at these two locations in Figs. 7 and 8. Since filling was completed before the commencement of settlement monitoring, see Fig. 7, and piezometers are available, the computation of stress increments at SG-1 is straightforward. On the other hand, the computation of stress increments at E-1 requires the information given in Figs. 5 and 6. As can be noted that although SG-1 and E-1 are more than 500m apart, excellent agreement with observations was obtained at both places. Not only surface settlements, the computed settlements at a depth of 50m agree with the recordings equally well. This provides the full confidence on the proposed procedures despite the many simplifications made. One thing worth mentioning is that the subsoils below a depth of 50m have N-values between 30 and 50 and yet readings show settlements of 500mm at SG-1 where the fill is about 4m in thickness and 1000mm at E-1 where the fill is about 10m thick.

Calculations were also made with pumping stage removed and the results are compared with those with pumping effects included in Fig. 9. The effects of pumping on settlements are readily

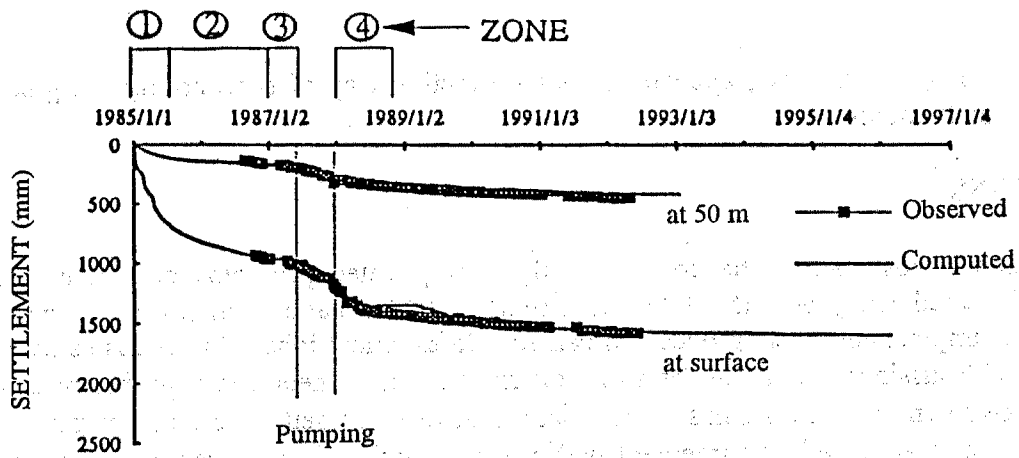


Fig. 7 Observed and Computed Settlements at SG-1

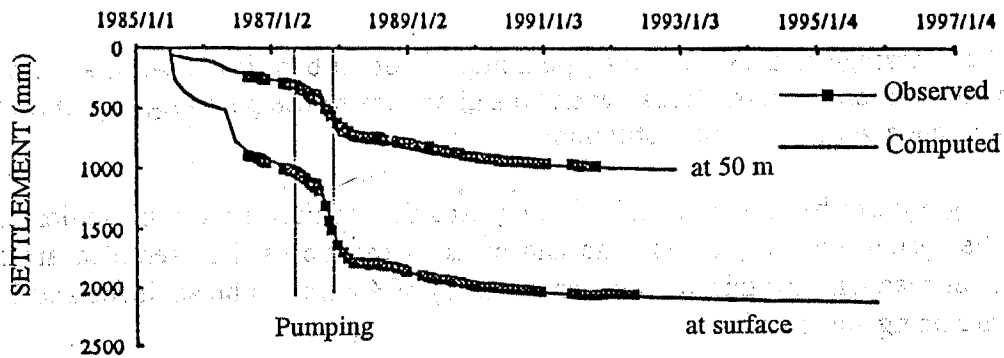


Fig. 8 Observed and Computed Settlements at E-1

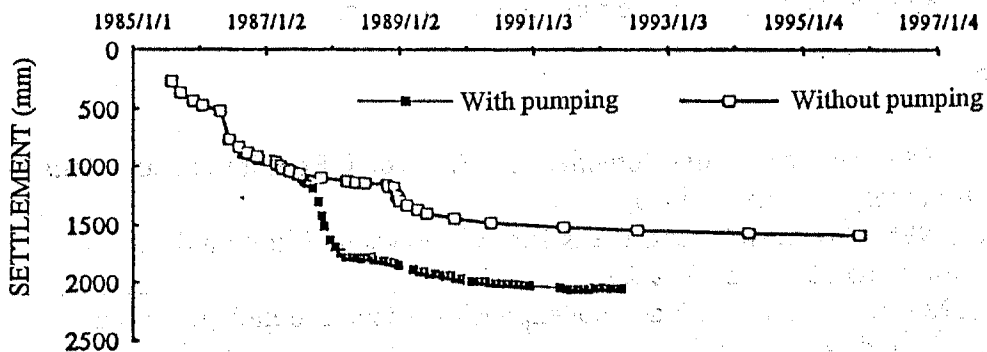


Fig. 9 Effects of Pumping on Ground Settlements at E-1

apparent. Pumping, in this case, appears to be an effective way of surcharging the ground to induce ground settlements.

CONCLUSIONS

The above discussions lead to the conclusion that complicated problems do not necessarily require sophisticated analyses. If all the construction details have been properly considered, most of times, simplest analytical procedures can also do excellent jobs. In the case studied, the combination of Boussinesq equation for stress distribution, the Theis non-equilibrium equation for water drawdown, and Terzaghi's consolidation theory for settlement computation gives results which are in an excellent agreement with the observations. All these are classical and fundamental formulations available in textbooks.

The excellent agreement between the theoretical solutions and observations not only proves the validity of the theories and the analytical procedures adopted in the study, but also illustrates the application and confirms the field performances of the various geotechnical instruments installed at the site.

Another important message to pass on is that, pumping is not all bad, it did work as surcharge and speed up consolidation process. It may even be a good idea to use pumping as a mean to let settlements to complete while the land is still unoccupied.

Global Positioning System has the potential of being used for monitoring ground settlements in large areas. The system not only saves time and costs, it can be used in remoted areas and provide continuous readings. At this moment, an accuracy of 40mm can be achieved and further improvements are being attempted.

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