SOIL IMPROVEMENT WITH PRELOADING AND VERTICAL DRAINS

by

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Soil improvement with preloading and vertical drains

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SYNOPSIS The use of prefabricated drains for accelerating the rate of consolidation of a soft compressible silty clay at a reclamation project in Taipei is described. The project site, covering an area of approximately 40 hectares, was an old abandoned river channel underlain by a layer of sludge and 20 to 40m of soft silt clay. The site was reclaimed for new town development by hydraulic fills. Under the 2 to 4m of fill, the total settlement was estimated in the order of over 60cm and will take more than 20 years. A detailed study was carried out to evaluate the feasibility of reclamation. Soil improvement with vertical prefabricated drains was adopted for accelerating the rate of consolidation of the compressible soil stratum. A total of over 1.2 million linear meters of drains was installed over the site. Monitoring records indicate that 6 to 10 months after installation of the drains, 75 to 95 per cent of the excess pore pressures has dissipated and the degree of consolidation ranged between 74 to 95 per cent. The estimated residual settlements were less than 15cm which met with the requirement for the new development.

INTRODUCTION

The Keelung River Abandoned Channel (KRAC) is a section of the old Keelung River passing through Shih-Ling and Shi-Tse Districts in the suburb of the Taipei City. Due to its lowlying level, the area was frequently flooded. As a part of the flood control measures in 1965, the Taiwan Water Conservation Bureau has diverted the flow of the Keelung River by straightening the river channel and abandoning the winding section at the foot of the Chi-Tan Mountain as shown in Fig.1.

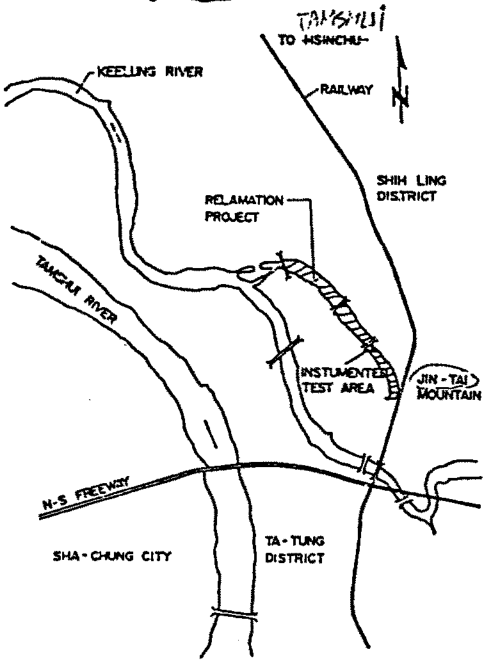


Fig.1 Site Location of the KRAC Reclamation Project

The abandoned channel is about 200m wide and 2km long with a total area of over 40 hectares. During the past twenty years, part of the area became a dumping ground for construction wastes and household disposals and created serious environmental problems. For a number of years the City Government was considering an effective way of reclaiming that area. In 1979, the Government decided to develop the area into a new town with public housing and associated facilities. Moh and Associates Inc. (MAA) was engaged by the Public Works Department to carry out a feasibility study to evaluate the geotechnical problems which would associate with development of the area, in particular problems related to reclamation by filling of such a vast area. The study included site investigation, laboratory testing, methods of filling, material source evaluation, and design of temporary and permanent drainage facilities. In order to reclaim the KRAC area for a new town development about 2 to 4m of fill would have to be placed over majority of the 40 hectares area. Two major problems which must be resolved for the reclamation work were the presence of a layer of sludge and a thick layer of low strength high compressibility silty clay underlying the river bed. Several methods of soil improvement were evaluated for treating the sludge and the soft clay. On the basis of the feasibility study, the use of preloading in conjunction with prefabricated drains was adopted for the project. A total of over 1.2 million linear meters of prefabricated drains was placed over the reclaimed area. MAA was then engaged by the turnkey contractor Ret-Ser Engineering Agency to undertake the responsibility of design and performance evaluation.

SUBSOIL AND GROUNDWATER CONDITIONS

Subsoil Conditions

Similar to the subsoil profile of the Taipei Basin (MOH and OU, 1979), the soil profile in the KRAC area can be divided into six layers with a typical profile shown in Fig.2.

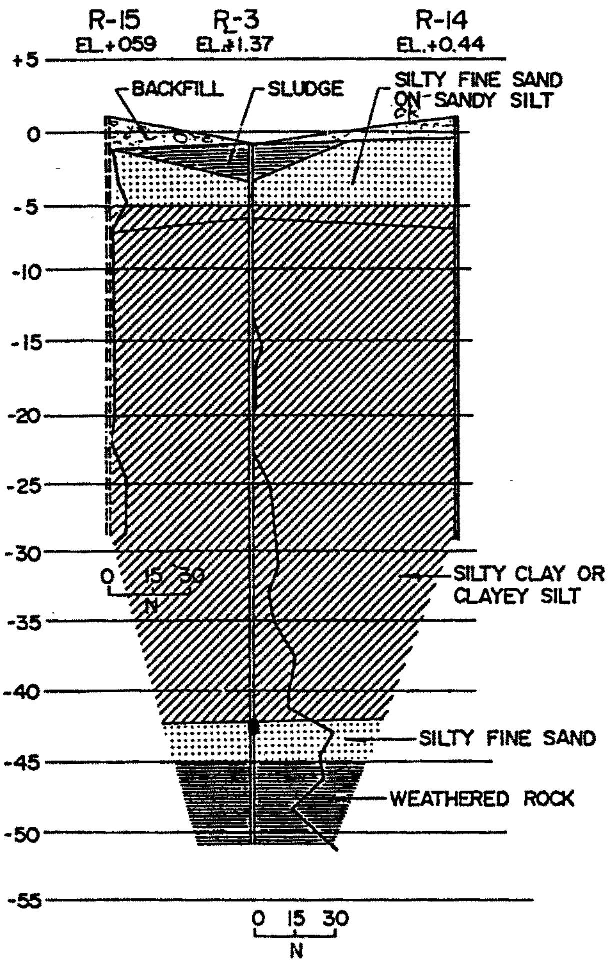


Fig.2 Typical Soil Profile at the KRAC

1. Backfill

At the time of the site investigation, the two banks of the channel and a large portion of the area were covered with miscellaneous backfill consisting of construction wastes, concrete blocks, bricks, etc. The fill was rather loose and varied from 2 to 6.6m in thickness. In areas where no fill was dumped, there was a layer of soft clay top soil of about 1 to 2m in thickness.

2. Sludge

In the middle of the channel which was under water for the past 20 years, the river bottom was covered with a layer of sludge varying in consistency from semi-liquid to very soft and 1.5 to 4.0m thick. The sludge was very soft, dark brown to black in color, and had moisture contents varying from 300 to 500 per cent. The solid content of the sludge was primarily of sand and silt sizes with very small amount of clay size particles. Very little sludge was found underlying the backfilled areas.

3. Silty Fine Sand

Immediately below the backfill or the sludge was a layer of silty fine sand varying from 2 to 10m in thickness. This sand was in a very loose condition underlying the sludge and became loose to medium dense at locations where backfill existed.

4. Silty Clay

Underlying the silty fine sand was a layer of soft silty clay with an average thickness of about 22m. In certain areas, this clay was as thick as 35m. Due to its relatively large thickness, low strength and high compressibility this soil stratum played the most important role in the feasibility of reclamation of the KRAC. A large number of field and laboratory tests was carried out on soil samples taken from this stratum to evaluate the properties of this soil layer. They are summarized as below:

(i) Moisture content - The natural moisture contents of the silty clay fell in the range of 25 to 50 per cent. In most cases, the natural moisture content was near and higher than the liquid limit. In areas where there were backfills, the moisture contents tended to be lower than that in areas without backfilling. This indicated that some consolidation had occurred under the backfill load.

(ii) Shear strength - The $s_u/\bar{\sigma}_{vo}$ ratio of this silty clay was only 0.12 to 0.20. The sensitivity value varies from 4 to 9, with the highest value up to 15, indicating that the soil is quite sensitive.

(iii) Compressibility - The value of the compression index as determined from one dimensional consolidation tests varied from 0.2 to 0.4. The clay underlying the backfilled area was under-consolidated whilst those in the middle of the channel were slightly over-consolidated due to erosion of the overburden material caused by water flow.

(iv) Permeability - The silty clay was quite impermeable. The coefficient of permeability in the vertical direction was determined to be about 10^{-6} to 10^{-8} cm per sec. and that in the horizontal direction was about 1 to 6 x 10^{-6} cm per sec. This higher permeability in the horizontal direction would play an important role in any soil improvement work.

5. Silty Fine Sand

Underlying the soft silty clay is a thin layer of silty fine sand varying from 2 to 9m in thickness. The average SPT-N value of this soil layer was about 20 to 30. It varied from medium dense to very dense with N values some times larger than 50.

6. Weathered Rock

At El-35 to El-40, weathered rock or rock formation was encountered. The rock formation varies from sandstone to shale and the degree of weathering varied considerably over the entire area.

Groundwater Conditions

Figure 3 presents the piezometric pressure distribution of the groundwater over the site based on measurements from piezometers installed during the initial site investigation in 1980 and additional site investigation carried out just prior to the reclamation filling in 1983. The perched groundwater table was at about the same level as the water level in the channel (i.e., El±0). In the area where backfill was present, the piezometric pressures were still higher than the static water pressure which indicated that the subsoil was undergoing consolidation under the backfill loading. In the unfilled channel area, the piezometric pressures although increased with depth, were always below the static pressure which is a common phenomenon in the Taipei Basin due to deep well pumping (MOH and OU, 1979).

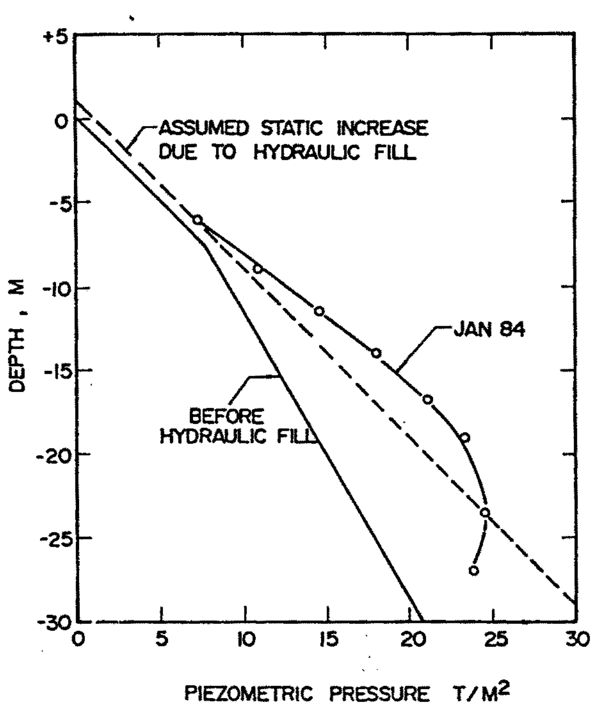


Fig. 3 Distribution of Piezometric Pressure vs Depth

SOIL IMPROVEMENT STUDY AND DESIGN

Soil Improvement Study

As pointed out in the Introduction, the major problems for developing the KRAC by reclamation were the presence of the sludge and the highly compressible soft silty clay layers underlying the site. Several methods were considered and evaluated for treatment of the sludge including complete replacement by excavation, dewatering by drying, use of geotextiles and chemical stabilization. Results of laboratory tests indicate that the sludge contained only 8 to 17 per cent organic matter and the major solid constituents were sandy and silty size particles. Reclamation of the area would be carried out by hydraulic fill method by pumping sands from the nearby Keelung River and Tamshui River. With the high water content of the hydraulic fill (water to sand ratio about 6 to 1), a large part of the sludge would flow away with the water. The remaining sludge would mix with the sand. Laboratory consolidation test results of mixtures of sand and sludge of different proportions show that consolidation of the mixtures was completed within a very short period of time under a small overburden pressure as illustrated in Fig.4. Since the thickness of the sludge over the site was relatively small, even some differential settlements which might occur would not cause any significant problem. The soft silty clay stratum presented three problems. They were:

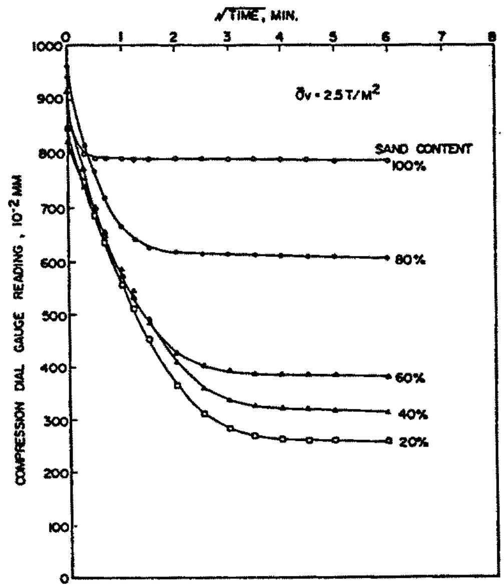


Fig. 4 Consolidation Behavior of Sludge-Sand Mixtures

(i) the average thickness of the clay was about 22m with maximum up to 35m,

(ii) the soil was extremely soft with SPT-N values varying from 0 to 2, and

(iii) the soil would undergo large settlement under the proposed reclaimed fill load and the settlement would take a long time to complete.

In order to be able to develop the reclaimed area as soon as possible, it was necessary to improve the characteristics of this soil layer by accelerating the rate of consolidation under load and increasing the strength. The use of sand drains and lime columns at this site was considered to be limited due to the deep depth of improvement required.

Prefabricated band drains were considered to be more preferable for accelerating the consolidation rate of the thick soft silty clay underlying the site.

Due to variation in the extent of backfills, the entire site was subdivided into three major zones as shown in Fig.5. Analyses were carried out to evaluate the rates of settlement under the following conditions:

(i) without any soil improvement,

(ii) using sand drains of 45cm diameter, 15m long at 2m spacing, and

(iii) using 10cm wide prefabricated drains, 30m long at 1m and 3m spacings. Figure 6 presents the estimated time-settlement curves for the average soil conditions in Zone II with different treatment methods. The average thickness of the silty clay in this zone is 32m and the fill is 5m. Table I summarizes the time required to reach different amount of residual settlements for the different conditions. The efficiency of using prefabricated drains for accelerating consolidation of the compressible silty clay layer is clearly demonstrated by the results of the analyses.

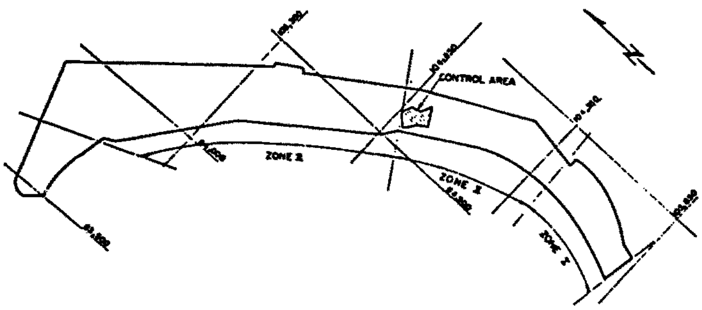
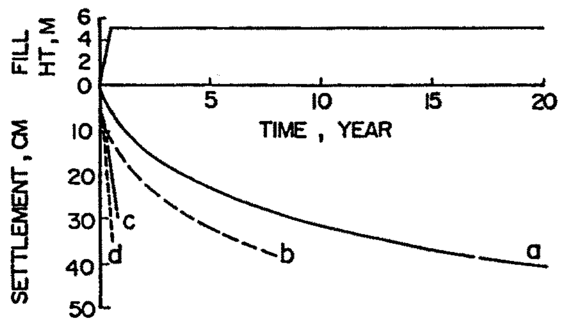


Fig.5 Zoning of the Reclaimed Area



a. NO IMPROVEMENT
b. 15M LONG SAND DRAINS AT 2M SPACING
c. 30M LONG PREF DRAINS AT 3M SPACING
d. 30M LONG PREF DRAINS AT 1M SPACING

Fig.6 Estimated Time-Settlement Relationships in the Middle of the Abandoned Channel of Zone II

Table I
Estimated Time Required
For Various Residual Settlement
(Zone II)

Fill Height 5.0 m		Time Required, years			
		No Soil Improvement	15 m long Sand Drains at 2 m Spacing	30 m long Prefab. Drains at 3 m Spacing	30 m long Prefab. Drains at 1 m Spacing
Residual Settlement	10 cm	12.5	6.5	0.96	0.41
	15 cm	8.5	4.2	0.72	-
	20 cm	5.9	2.7	0.59	-

Soil Improvement Design

The basic criterion for the design of the soil improvement scheme was that the average residual settlement under the proposed fill of 2 to 4m (i.e., up to El±3m) at the time when the reclaimed land is delivered to the Government should not be more than 15cm. The land was to be delivered to the Government six months after completion of all the drain installations or 20 months after starting of the reclamation. On this basis, prefabricated drains at 1.5m and 2.0m spacing were adopted. According to the new town development plan, approximately 5.2 per cent of the reclaimed land will be used for parks and 0.4 per cent for parking. In these areas, less stringent requirements for residual settlement could be tolerated.

Due to variations in the depths of the silty clay layer underlying the site, and variation in the amount of backfill materials present, the three major zones were further subdivided into 10 subzones. The depths and spacings of drains in each subzone were designed accordingly Majority of the drains were designed to extend to about El-20 to El-22 which was about mid-depth to two-thirds depth of the silty clay layer.

There are many types and makes of prefabricated drains available on the market, such as Alidrain and Geodrain from Sweden, Colbond from the Netherlands, Bando drains and PVC drains from Japan. Each make has its special characteristics and each claims that they are the best. Since the total quantity of drain materials involved in the project was very large, in excess of 1.2 million linear meters, and since it is necessary to drive the drains to a depth of 30m, strict specifications and prequalification requirements were prepared. One of the emphasis was placed on performance records of the drains in deep soft soils. Some of the drains were reported to behave unsatisfactorily under pressure due to collapse of the filter layer or the corrugation of the core. Laboratory tests were carried out on a number of different types of drains. The specifications adopted for material's requirements are listed in Table II. The selection of the drain material was made by open tender of prequalified drain makes. Bando Chemical Board from Japan won the tender.

Table II
Specifications for
Prefabricated Drains

Properties	Specification Requirements
Tensile Strength, kg/10 cm width	>70
Elongation at 70 kg/10 cm, %	<15
Permeability of Filter layer cm/sec	1×10^{-3} to 2.5×10^{-5}
Permeability of Drains cm/sec Longitudinal	$>10^{-1}$ under 3 kg/cm^2 pressure
Permeability of Drains in Soil Mass	$>10^{-2}$ under 3 kg/cm^2 pressure
Drain Size, cm	
thickness	-
width	8.12
filter thickness	-
filter width	-

CONSTRUCTION

Reclamation

The reclamation work for the KRAC was carried out by two methods. In Zone I, the reclamation was done mainly by landfills since a major part in this zone was already backfilled with construction wastes and miscellaenous dumps. Hydraulic sand fills were dredged from the nearby Tamshui River and pumped through 80cm diameter, 6km long pipes to Zones II and III. The ratio of sand to water in the hydraulic fill was about 1 to 6. A total of about 12 million cubic meters of hydraulic fill was dredged and placed on the site within a period of about 4 months.

Installation of Prefabricated Drains

Installation of the prefabricated drains was commenced immediately after completion of the hydraulic fill. A total of about 1.2 million linear meters of drains was installed at spacings of 1.5 or 2.0m and to depths from El-20 to El-22.9. The length of each drain varied from 24 to 27m in accordance with the variation of the ground elevation and the subsoil profile. The installed depths of the drains were very close to the original design estimate. The drains, 10cm wide and 0.3cm thick, were installed with a vibratory leader. In certain areas where the thickness of the hydraulic fill was relatively large, penetration of the drains was assisted by either predrill or water jetting or both.

SOIL IMPROVEMENT PERFORMANCE EVALUATION

Instrumentations

Since this project was the first one in Taiwan to install prefabricated drains to such deep depth and with such a large quantity, it was originally planned to carry out a test section to evaluate the drain performance and to determine the optimum spacing. An area of approximately 5,500 sq m in Zone II was selected for such a purpose, designated as Control Area on the site plan in Fig.5. Two different drain spacings, that is, 1.25m and 1.5m, were used. Instrumentations including surface settlement plates, deep settlement points, pneumatic and hydraulic piezometers were installed as shown in Fig.7. In this Control Area, additional borings, samplings, SPT, Dutch Cone penetration soundings and laboratory testings were carried out immediately after the completion of the fill operation as well as several months after the installation of the drains.

Due to practical difficulty and time constraint, it was not possible to hold the filling operation over the entire site until completion of the test results at the Control Area. However, filling and drain installation were first carried out in the Control Area. In the Control Area, placement of the fill was started in early November 1983 and reached the design elevation plus surcharge in about 45 days. The fill with surcharge was left to consolidate under its own weight for about 8.5 months before installation of the drains. Data obtained from the instrumentations in the first few months subsequent to the filling operation was fully utilized to determine the design spacing of drains for the entire project. Moreover, for evaluation of the overall performance and effectiveness of the prefabricated drains at this project, a large number of instrumentations was installed over the entire site. These instruments were designed to determine the rate and amount of settlement of the compressible subsoils under the reclamation fill, the changes in porewater pressures and the effect of the fill on existing structures situated along the banks of the abandoned channel. The instrumentation program included:

(a) Land area within the abandoned channel - 6 deep settlement rods, 6 surface settlement plates, 6 pneumatic piezometers, 46 surface settlement points, 8 hydraulic piezometers and 6 observation wells.

(b) Water covered area within the abandoned channel - 33 deep settlement rods, 29 surface settlement plates, 30 pneumatic piezometers and 5 hydraulic piezometers.

(c) Land area along the banks of the abandoned channel - 15 hydraulic piezometers and 35 surface settlement points.

Majority of the instruments were installed prior to the hydraulic filling of the site.

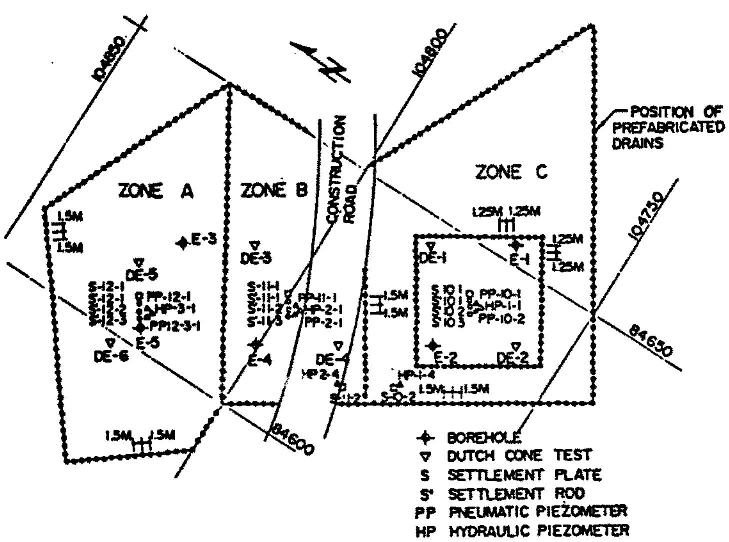


Fig. 7: Location Plan For Instrumentations in the Control Area

Effect of Soil Improvement on Soil Properties

To evaluate the effectiveness of the soil improvement scheme, additional soil borings, samplings, in-situ and laboratory testings were carried out both in the Control Area as well as in the overall site. The original design was planned to have the Control Area working as the pilot test area. Results obtained from the control tests were to be used for the final design of the entire soil improvement scheme. However, due to practical constraints including time, operation and contractual difficulty, the hydraulic filling and installation of the prefabricated drains were carried out continuously and simultaneously over the entire site including the control area.

(1) Silty clay layer - The original natural moisture content of the silty clay layer, which is the soft and compressible soil layer to be improved, varied from 30 to 50 per cent. Several months after placement of the hydraulic fill, the moisture content dropped to the range of 25 to 48 per cent. The moisture content further decreased after installation of the drains due to dissipation of the excess porewater pressure as illustrated in Fig.8. The average undrained shear strength of the clay above El-15 increased by approximately 50 per cent, in the order of 1.0 to 1.5 tons per sq m (Fig.9), and the coefficient of volume change decreased from 30 to 40 sq cm per kg to about 20 to 35 sq cm per kg due to the soil improvement (Fig.10). Although the major part of improvement of soil properties as determined from laboratory tests on undisturbed samples appeared to occur in the upper half layer of the clay stratum, cone penetration results however show that the effect of soil improvement extends as far as El-35 which is near the

bottom of the clay layer, Fig.9.

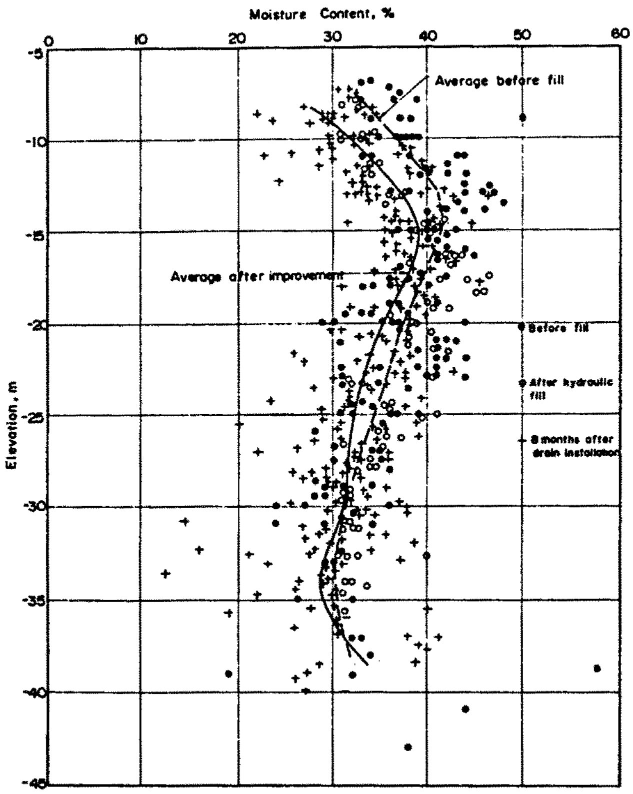


Fig. 8 Variations of Natural Moisture Content with Depth Bfr and After Soil Improvement

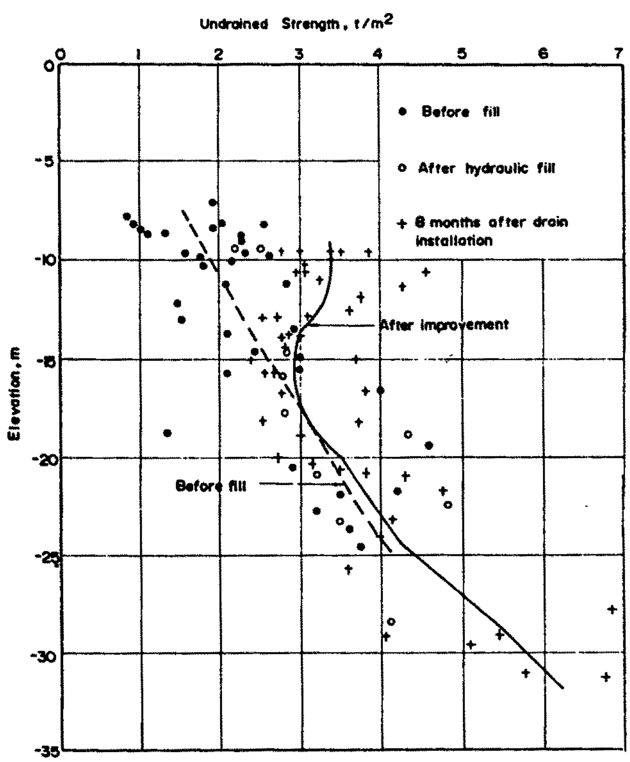


Fig.9 Undrained Shear Strength of the Silty Clay Before and After Soil Improvement

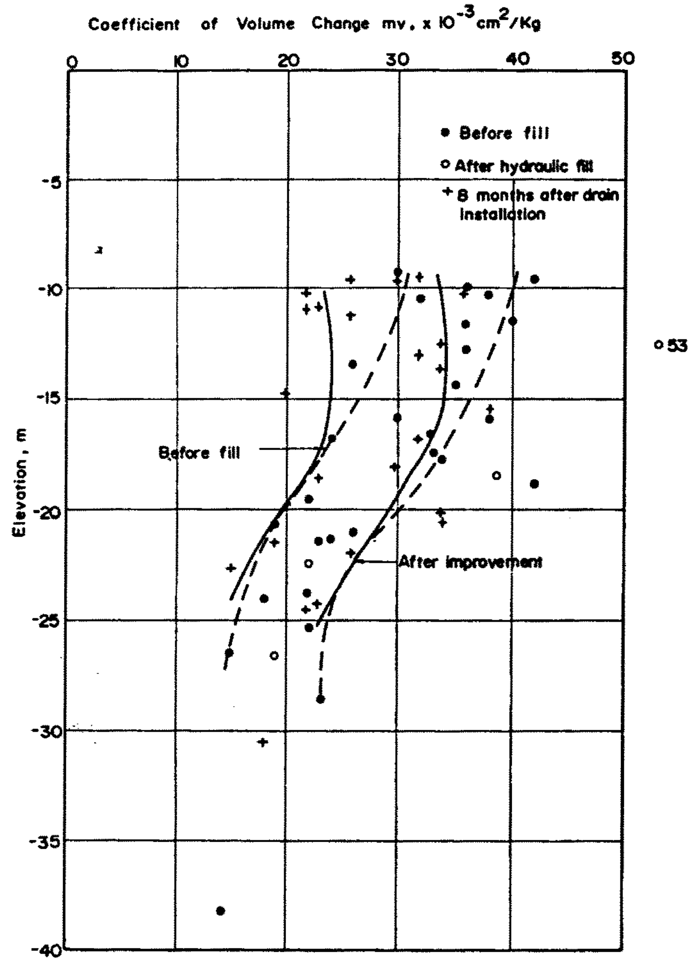


Fig.10 Compressibility of Silty Clay Before and After Soil Improvement

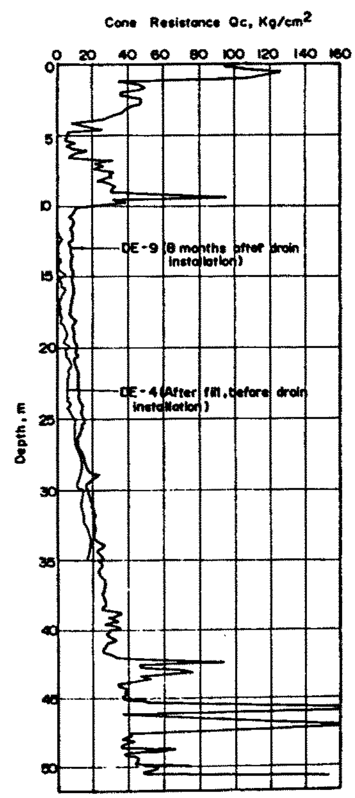


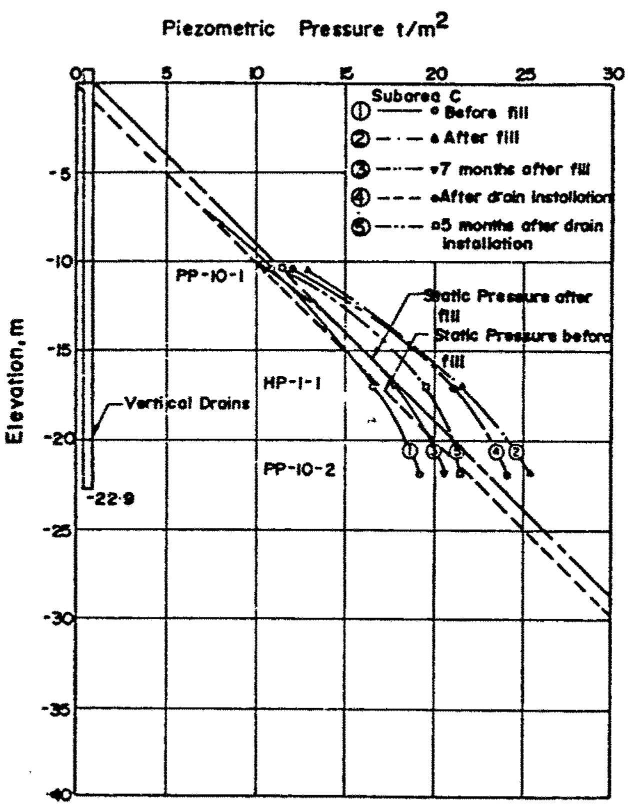
Fig. 11 Cone Penetration Resistances Before and After Soil Improvement

(2) Sludge - Due to the squeezing and displacing action of the hydraulic fill, the sludge layer at the river bed reduced to only about 1.5 to 2m thick. The natural moisture content decreased from 300 to 500 per cent to only 30 to 55 per cent for the sandy-silty sludge and to 70 to 95 per cent for the finer portions.

Effect of Soil Improvement on Groundwater Conditions

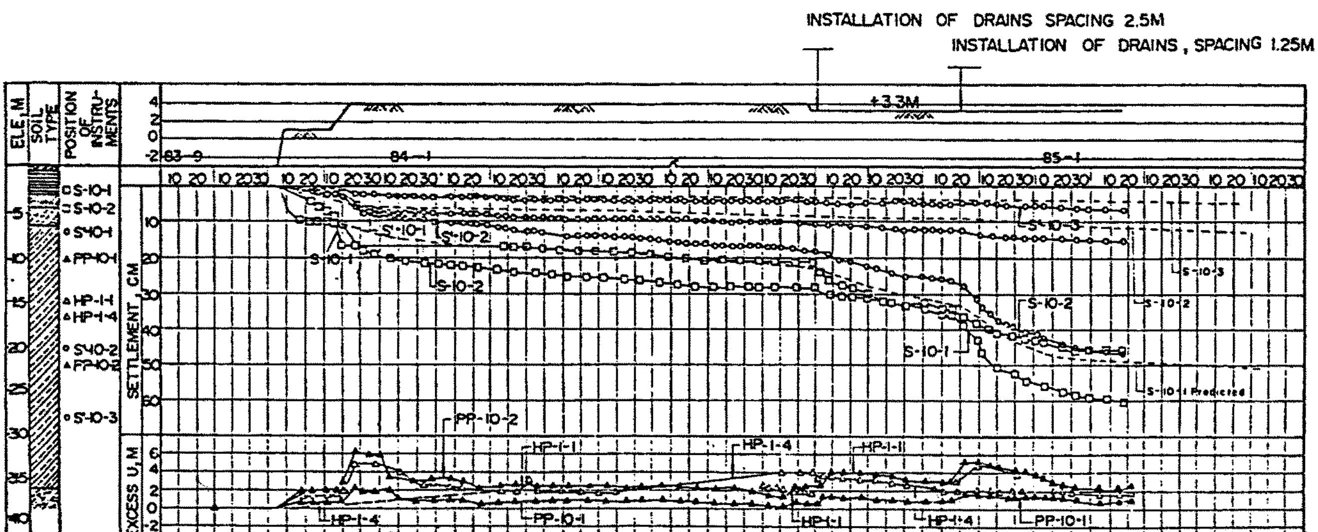
Figure 12 illustrates the changes in the groundwater conditions due to the placement of the fill and installation of the drains. The apparent groundwater table at the site before any fill was placed was at about El±0m as shown in Fig.3. Immediately after placement of the hydraulic fill and also after installation of the drains, the apparent water table rose to about El+0.5m to +2.0m. The watertable stabilized quickly and reached a level between El+0.3m to +1.2m which is similar to the groundwater level in areas surrounding the reclaimed area.

The piezometric levels in the silty clay layer increased quickly due to placement of the fill. With time, the excess pore pressure dissipated. Installation of the prefabricated drains again increased the pore pressure, sometimes to a level even higher than that caused by the fill. This development of the excess pore pressure can be attributed to the vibration effect during the installation of the drains. The excess pore pressures dissipated fairly quickly with time. Figure 12 shows that 5 months after installation of the drains, the porewater pressure distribution approached static condition. However, they were still higher than the pore pressures before the reclamation. Whether the drains will cause a permanent increase in the porewater pressure at the site where the groundwater was originally in an underpressured state is a problem of concern. Long term monitoring of the piezometric pressure regime is needed. The rate of dissipation of excess pore pressures is further illustrated in Fig.13.



← Fig.12 Variations of Piezometric Pressures Due to Fill and Drains

Fig.13 Pore Pressure and Settlement Record in Control Area C



Settlement Rate and Residual Settlement

On the basis of instrumentation monitoring data, the effectiveness of the soil improvement scheme was evaluated in terms of rate of settlement. Detailed evaluation of these three items was made at various sections where either the height of fill was different or the subsoil profile varied. A summary of the evaluation is listed in Table III. Practically over the entire site, the estimated total residual settlement is less than 15cm at a time of 6 to 11 months after installation of the vertical drains. Figure 13 shows the settlement and pore pressure records obtained in Subarea C of the Control Area. From this figure, it can be observed that installation of the prefabricated drains has greatly accelerated the rate of consolidation of the underlying soils. Within a four-month period, the degree of consolidation increased from about 20 per cent, which took almost 8.5 months under the fill load, to about 60 to 80 per cent.

Effect of Drain Spacing

Figure 14 shows the settlement records at the top of the silty clay layer in the three subareas of the Control Area. At the end of eight months after placement of the hydraulic fill and prior to installation of any drains, the average rate of settlement was about 0.04cm per day in all three subareas. The effect of installation of drains were:

(a) Subarea A - Drains were installed at 1.5m spacing. Ten days after the installation, the rate of settlement increased to about 0.45cm per day which was about a ten-fold increase.

(b) Subarea B - Drains were placed at 1.5m spacing on one side and no drains on the other side. Ten days after installation, the settlement rate was about 0.16cm per day, that is a four-fold increase.

Table III
Summary of Prefabricated Drains on Settlement and Pore Pressure

Zone	Time Elapsed After Installation of Drains, Months	Degree of Consolidation of Silty Clay Layer, %	Degree of Dissipation of Excess Pore Pressure, %	Estimated Residual Settlement, cm
II	6 - 8	74 - 93	70 - 90	<15
III	7 - 11	74 - 95	75 - 95	<15*

* Except for a few isolated small areas, the residual settlement was about 17 cm.

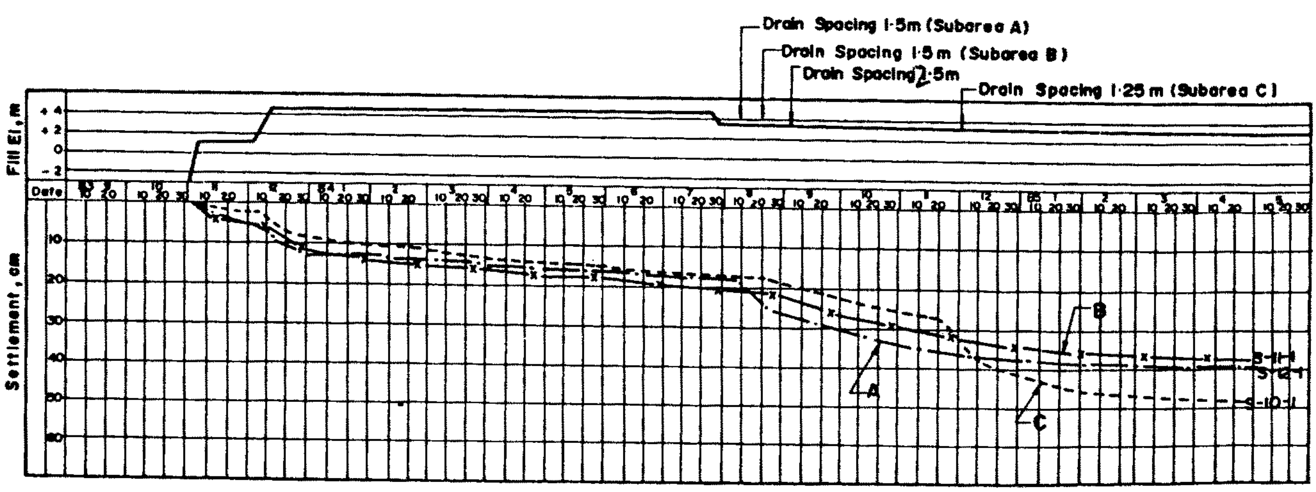


Fig.14 Effect of Drain Spacing on Settlement Rate

(c) Subarea C - Drains were spaced at 2.5m. Ten days after installation, the average rate of settlement was about 0.15cm per day. When additional drains were installed and the spacing was about 15-fold increase over the rate before the drains were installed.

The above observations clearly demonstrate the effect of drain spacing. At the end of April 1985, that is, five months after the placing of additional drains, the total settlement in subarea C was about 8cm more than that in subarea B.

Effect on Surrounding Areas

One of the factors which should be considered in any large scale reclamation and improvement work is the effect on surrounding environment. For the KRAC reclamation project, the environmental factors which were evaluated included drainage, groundwater regime and settlement of existing structures. Temporary drainage facilities were constructed around the reclaimed area to drain off the large amount of water from the hydraulic fill to prevent any risk of flooding and environment pollution. After the reclamation work, permanent drainage facilities were constructed to take care of the drainage requirement for the proposed development.

Considerable amount of instrumentations including piezometers and settlement markers were installed in the surrounding area and on the existing structures. Piezometer monitoring data indicate that there were excess pore pressures in the order of 0.5 to 1.0 ton per sq m developed in the silty clay layer surrounding the reclaimed site due to the placement of the hydraulic fill. About 30 to 50 per cent of these excess pore pressure have dissipated in the approximately one year time after the filling. Settlement records indicate that the two banks of the KRAC settled about 1 to 2cm due to placement of the hydraulic fill and construction of drainage facilities, of which 0.06cm was due to general subsidence of the area. Effect of the fill and drains on surrounding existing structures was found to be negligible with estimated maximum long term settlement in the order of 2 to 3cm.

ACKNOWLEDGEMENTS

The project described in this paper was sponsored by the Engineering Maintenance Bureau of the Taipei Public Works Department through the Ret-Ser Engineering Agency. The writers wish to acknowledge the assistance given by the many engineers of the two organizations who have rendered assistance during the execution of the project and helped in collecting instrumentation data. Special thanks are due to Messrs Benjamin Chi, Chief Engineer, C.P. Lai, Project Engineer, and resident engineering staff of Ret-Ser; Director and Deputy Director of the Engineering Maintenance Bureau of Taipei PWD. Acknowledgements are also due to the writers' many colleagues who were involved in the project, specially Messrs Y.G. Li and C.H. Wang.

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CORRIGENDUM

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Settlement Rate and Residual Settlement

On the basis of instrumentation monitoring data, the effectiveness of the soil improvement scheme was evaluated in terms of rate of settlement, rate of dissipation of excess pore pressures, and amount of residual settlement. Detailed evaluation of these three items .....

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(c) Subarea C - Drains were spaced at 2.5m. Ten days after installation, the average rate of settlement was about 0.15cm per day. When additional drains were installed and the spacing was reduced to 1.25m, the settlement rate further increased to about 0.60cm per day which was about 15-fold increase ......