Soil Improvements of an Inhomogeneous Reclaimed Ground

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SYNOPSIS: A coal storage yard for an electric power plant was to be constructed on reclaimed land in northern Japan. As the reclaimed land consisted of loose sand and soft silt, a deep well excavation method, a dynamic compaction method and a sand compaction method were selected to improve clayey grounds, sandy grounds and intermediate grounds, respectively. After the improvement, no obvious settlement and no liquefaction has been induced.

INTRODUCTION

In Japan, though much land has been reclaimed, more reclaimation is planned. In reclaiming land, the following two geotechnical conditions must be considered :
(1) Filled soil is very loose or very soft. Therefore, in general, the reclaimed land must be improved by some method.
(2) Sandy soil and clayey soil are distributed non-uniformly in reclaimed land. Different methods must be applied to improve sandy soil and clayey soil.

Tomatoh Coal Center, a coal storage yard for an electric power plant, was to be constructed at the eastern part of Tomakomai City, in northern Japan. The area of the yard was about 22 ha. Land was reclaimed along a coast for the coal storage yard by dredging soil from the sea bed of Tomakomai East Port. This reclaimed land was also faced to the above mentioned geotechnical problems. Thus, several studies, including many soil investigations and detailed analyses, were carried out to determine the optical methods of improving it.

OUTLINE OF TOMATOH COAL CENTER

A new coal storage yard, the "Tomatoh Coal Center", was built at the eastern part of Tomakomai City, in Hokkaido, as shown in Fig.1, to store coal and supply it to a neighboring electric power plant. The foundation ground for the Tomatoh Coal Center was constructed on a sea bed of about 7 to 10 m in depth by filling soils dredged from Tomakomai East Port. Two years were spent for the reclamation work. The area of the yard was 22 ha, almost 600 m in length and 400 m in width. Stock embankments of coal and rails of stack reclaimers were planned to be built on the reclaimed ground.

SOIL INVESTIGATIONS

After reclamation, soil investigations were carried out at about 40 points at intervals of about 60 m x 60 m as shown in Fig.2. Borings and standard penetration tests (SPT) were conducted at 15 points and Dutch cone penetration tests (CPT) were conducted at 25 points to supplement the

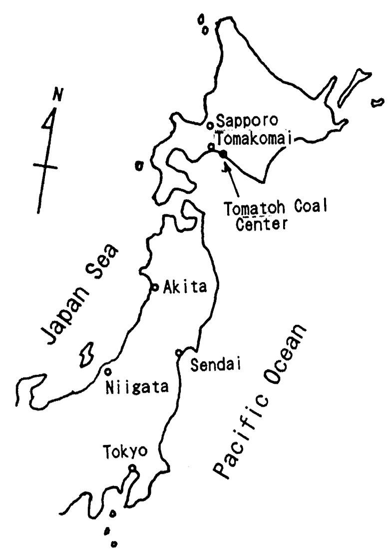

Fig. 1 Location of the Site

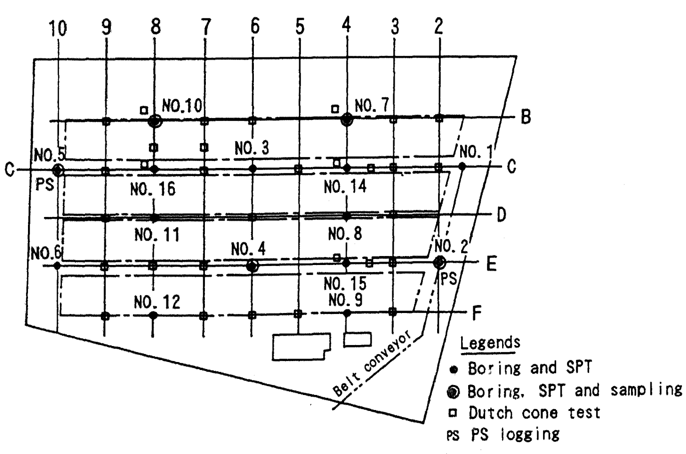

Fig. 2 Soil Investigations Conducted Before Improvement Work

borings. Undisturbed samples were taken at 5 boring sites and were subjected to unconfined compression tests, triaxial tests, consolidation tests, undrained cyclic triaxial tests and cyclic torsional shear tests. PS loggings were also carried out at 2 boring sites.

Fig.3 shows a typical soil cross-section estimated by the soil investigations. Reclaimed soil was deposited under the ground surface to a thickness of about 10 to 13 m. Alluvial sand layers or sandy gravel layers, which have high permeability, with thickness of 10 to 18 m, and diluvial soil layers with thickness of more than 20 m underlay the reclaimed soil. The reclaimed soil consisted of sand, silt and clay and was very loose or soft because a mixture of dredged soil and water was filled by means of scattering pipes and the reclaimed soil had not been consolidated or compacted.

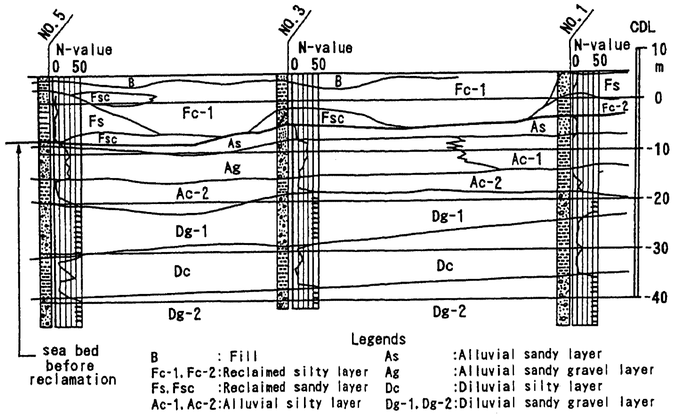

Fig. 3 Typical Soil Cross-Section

As the reclaimed soil consisted not only of sand but also of silt and clay, the ground had to be distinguished as predominantly (1) clayey ground, (2) sandy ground or (3) intermediate ground, to apply appropriate soil improving methods. Then, based on the definition shown in Table 1, the ground was distinguished as shown in Fig.4. Clayey ground, sandy ground and intermediate ground was distributed in the central part, outer part and intermediate part, comprising 75 %, 10 % and 15 %, respectively, of the total area.

Table 1 Areas of Clayey, Intermediate and Sandy Grounds

Ground	Classification	Area
clayey ground	Lc ≧ 5m	10.64ha
intermediate ground	2.5m ≦ Lc < 5m	1.92ha
sandy ground	Lc < 2.5m	1.39ha

Lc : thickness of reclaimed clayey layer

Fig.5 shows typical soil profiles of the three grounds. Silty layers, Layer Fc-1 and Layer Fc-2, predominated in the clayey ground and were very soft because the SPT N-values and CPT qc-values of the layers were almost zero. Layer Fc-1 was extremely soft. It was estimated that the consolidation of Layer Fc-1 by its own weight had not been finished, based on measurements by pore water pressure gauges. A sandy layer, Layer Fs, predominated in the sandy ground and was very loose because the SPT N-value of the layer was almost 5. In 1982, when the ground had been filled to just above the sea level, liquefaction occurred in the sandy ground during an earthquake. Based on detailed soil investigations and analyses (Saito, 1986), it was estimated that Layer Fs was liquefied. The peak surface acceleration at Tomatoh Coal Center was estimated as 100 gals. Table 2 shows typical soil properties of reclaimed soil layers.

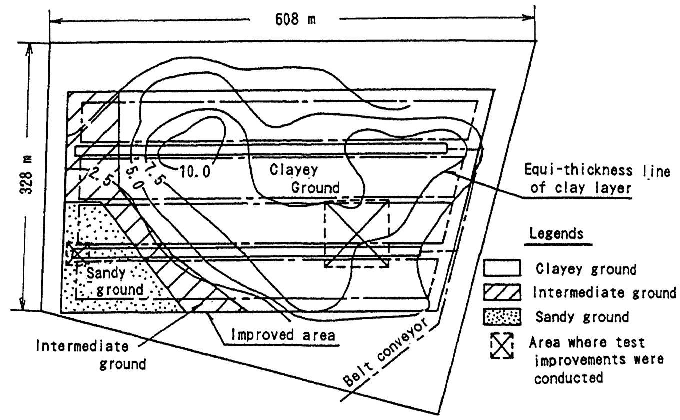

Fig. 4 Distribution of Sandy Ground and Clayey round

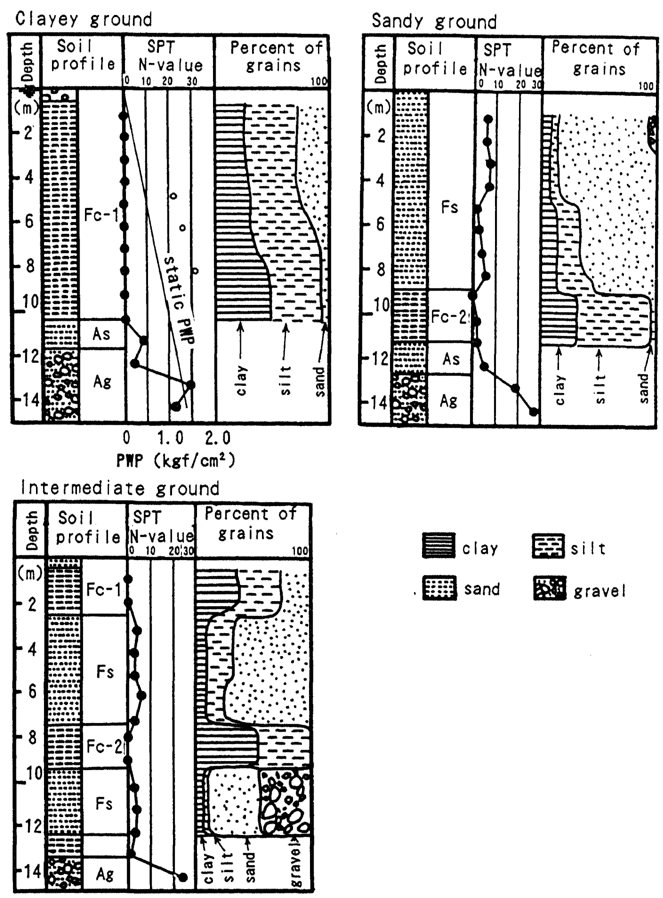

Fig. 5 Typical Soil Profiles of Clayey, Sandy and Intermediate Ground

Table 2 Typical Soil Properties

		ρ_s (g/cm³)	w (%)	FC (%)	D_{50} (mm)	Ip	e
Fc	FC-1	2.74	73	85	0.018	28	1.66
	FC-2	2.73	53	85	0.015	28	1.46
Fsc		2.75	39	47	0.083	NP	1.2
Fs		2.76	29	19	0.32	NP	1.13

NECESSITY OF SOIL IMPROVEMENT

Fig.6 shows an outline of facilities to be built at Tomatoh Coal Center. Four stock embankments of coal, each with a height of 12 m, a width of 50 m and a slope of 1 : 1.2, were planned to be filled. The coal would be stacked by stack reclaimers of 590 tons in weight. Two rails of stack reclaimers would be built between the stock embankments of coal. The loaded applied to the rails from the stack reclaimers was estimated at 20 tons per wheel, which was fairly heavy. A stability analysis for the stock embankments of coal and evaluations of bearing capacity and settlements of the ground under the stack reclaimers were conducted and compared with allowable safety factors, as shown in Table 3. Based on these studies, it was judged that all grounds had to be improved to open the yard by the deadline, with the following considerations:
(1) The clayey ground should be consolidated more, to support the facilities and reduce the settlement under the facilities.
(2) The sandy ground should be compacted so as not to liquefy during earthquakes.
(3) The intermediate ground should be compacted to support facilities and not to liquefy.

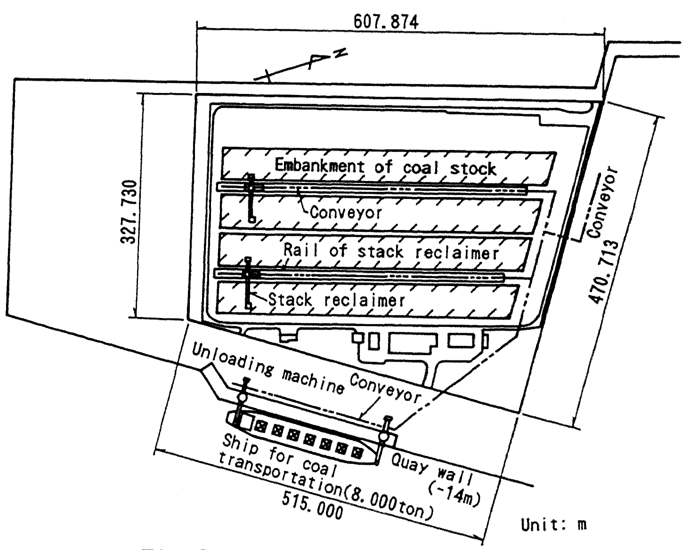

Fig.6 Outline of Facilities

Table 3 Design Values for Settlement, Sliding, Bearing Capacity and Liquefaction

		Embankment of coal stock	Stack reclaimer
Allowable settlement, Sa		100cm	12cm
Safety factor	Sliding, Fsa	Fsa=1.20(1.25*): ordinary condition Fsa=1.00 : during earthquake	–
	Ultimate bearing capacity, Fsa'	–	Fsa'=3.0:long term Fsa'=1.5:short term
Safety factor against Liquefaction, F_L		1.0	1.0

* Safety factor of the coal embankment, which is close to the rail of Stack Reclaimer

DESIGN FOR SOIL IMPROVEMENT OF CLAYEY GROUND

In Japan, the general way to improve a clayey ground is to apply a vertical drain and preloading jointly. In addition to this method, a deep well method was applied also in the clayey ground to the depth of Layer Ag, for the following reasons:
(1) By pumping up the water in the deep well, the water level in the ground decreases and effective overburden pressure in the silty layers increases. This must induce consolidation and increase the strength of the reclaimed clay as schematically shown in Fig.7. The design called for a water level reduction of 3 m. The increment of overburden pressure due to decreasing the water level by 3 m coincides with the increment of overburden pressure due to a preloading fill of about 1.8 m in height. Therefore, use of the deep well method allows a reduction in the height of the fill for preloading and reduce construction cost drastically.
(2) Problems of well resistance and mat resistance, which are encountered in a vertical drain method, can be avoided if a deep well method is applied jointly.
(3) The silty layers can be consolidated slightly before the preloading work by applying the deep well method. Therefore, trucks loaded with the soil for preloading can run on the clayey ground, and the soil for preloading can be filled without sliding.

Considering the effect of the deep well method, the height of the fill for preloading was designed as 4.0 m and 2.5 for the ground to support the rails for stack reclaimers and the stock embankments of coal, respectively. The pitch of the vertical drains was calculated based on Barron's theory, to reach 80 % consolidation within 60 days. In this pitch, the residual settlement was evaluated by the Δ-e method as 5.1 cm and 65 cm for the ground beneath the rails for stack reclaimers and the stock embankments, respectively. The estimated settlements and strength were examined by constructing a test embankment.

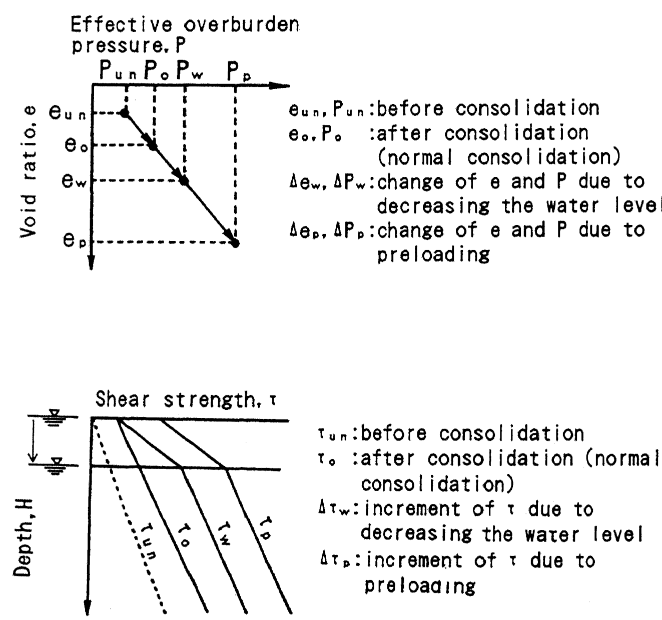

Fig.7 Schematic Diagram of Change of e, p and τ Due to Decreasing the Water Level and Preloading

DESIGN FOR SOIL IMPROVEMENT OF SANDY GROUND

After comparing the merits and demerits of several measures to counter liquefaction, the dynamic compaction method was selected for the sandy ground, because this method is economical and there was no possibility of damage due to the strong vibration and noise of dynamic compaction. In Japan, the method of estimating liquefaction strength used in the specification for highway bridges (Japan Road Association, 1980), which was derived from Iwasaki et al.'s formula (1978) with slight modification, and which uses SPT N-values, was commonly used. Therefore, comparing the undrained cyclic triaxial test results with Iwasaki et al.'s formula, the following special modified formula was derived to be applied to soil at the Tomatoh Coal Center :

$$R = R_1 + R_2 + R_3 \text{ -------(1)}$$

where, R : liquefaction strength (undrained cyclic strength ratio)

R_1 : $0.0882\sqrt{N/(\sigma v'+0.7)}$

R_2 : $0.225 \log(0.35/D_{50})$ for 0.02mm $\le D_{50} <$ 0.6mm, and -0.05 for 0.6 mm $\le D_{50} \le$ 2.0mm

R_3 : -0.07

Fig.8 compares tested R_2 with the data collected by Iwasaki et al. As the tested R_2 were almost 0.07 less than the average R_2 proposed by Iwasaki et al., R_3 was determined as -0.07. One reason that R_3 was necessary may be attributed to the short age of the reclaimed ground.

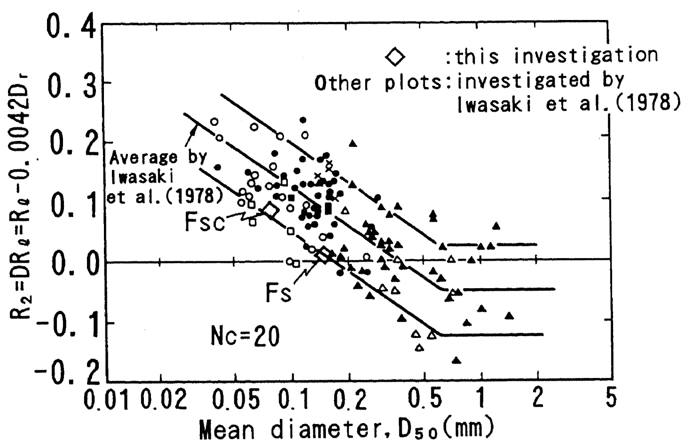

Fig.8 Relationships Between R_2 and D_{50}

On the contrary, the cyclic shear stress ratio, L, induced in the ground during earthquakes was evaluated by conducting seismic response analyses. The computer program used was "SHAKE". Input base acceleration for the analyses was determined by considering the return period of 100 years. The analyzed peak acceleration on the ground surface was almost 200 gals.

By calculating safety factors against liquefaction, F_L (=R/L) at several sites, design SPT N-values which satisfy the F_L shown in Table 3 were determined as shown in Fig.9. For dynamic compaction a 20 ton hammer, was dropped three times on each site from a height of 20 m. The effectiveness of this tamping was checked by conducting test tamping.

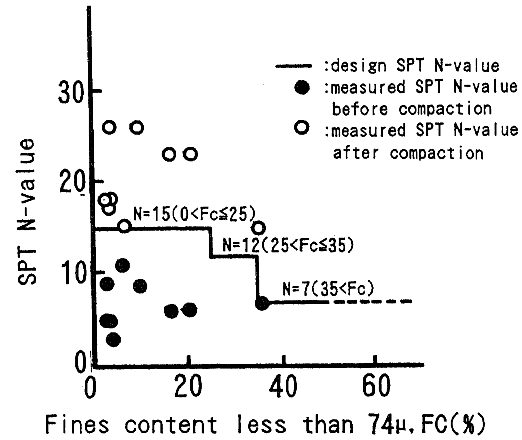

Fig.9 Comparison of Measured SPT N-values with Design SPT N-values

SOIL IMPROVEMENT OF INTERMEDIATE GROUND

In intermediate ground, Layer Fc had to be consolidated and Layer Fs and Layer Fsc had to be compacted. The design values used for the consolidation of clayey ground were used for Layer Fc and the values used to compact sandy ground were adopted for layers Fs and Fsc. To obtain both design values, the sand compaction method was selected. The dynamic compaction method was judged to be unsuitable because the energy produced by a dropping hammer decreases in a clayey layer and does not reach deep layers. An appropriate diameter for the sand compaction piles was designed as 70 cm, and these piles were arranged in squares with a pitch of 1.6 m.

TEST EMBANKMENTS IN CLAYEY GROUND

Two test embankments, illustrated in Fig.10, were built on the clayey ground to check the accuracy of the designed improving method. Heights of the embankments for the ground to support the stack reclaimer and the ground to support the stock embankments of coal were determined as 4 m and 2 m, respectively. Two kinds of vertical drains a paper drain and a packed drain, with pitches of 1.0 m and 1.2 m in square arrangement, respectively, were tested under both test embankments.

Fig.11 shows time-settlement curves. It is noted that settlements occurred due to the installation of the vertical drains only.

Fig.12 shows time-pore water pressure curves at Site P4. As shown in this figure, the pore water pressure also decreased due to the installation of the vertical drain. Therefore, it is estimated that the settlement occurred due to the dissipation of excess pore water pressure which had been created due to the weight of the soil.

As shown in Fig.11, the settlements 60 days after building the test embankments reached 95 % of the final settlements which were evaluated by a hyperbolic curve fitting method. Therefore, the improving methods were adequately effective and the designs for the improving methods were appropriate. Residual settlements estimated from Fig.11 in the ground to support the stack reclaimer and in that to support the stock embankment of coal were 5.7 cm and 43 cm, respectively. These values were within the allowable settlements shown in Table 3.

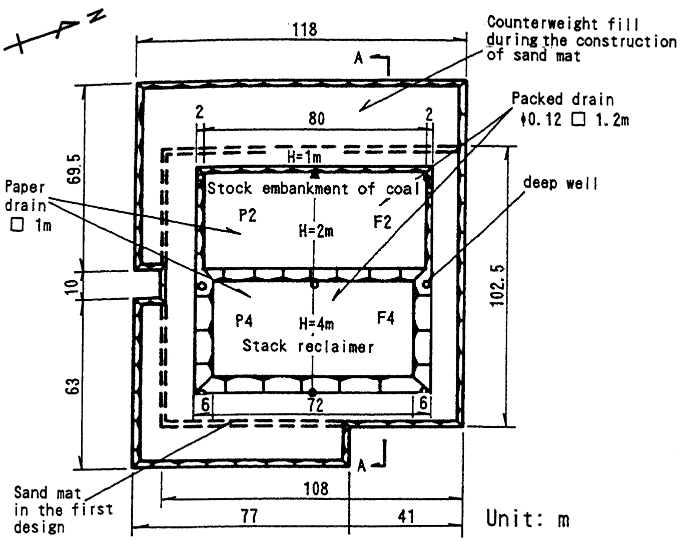

Fig. 10 Plane Figure of the Test Embankment

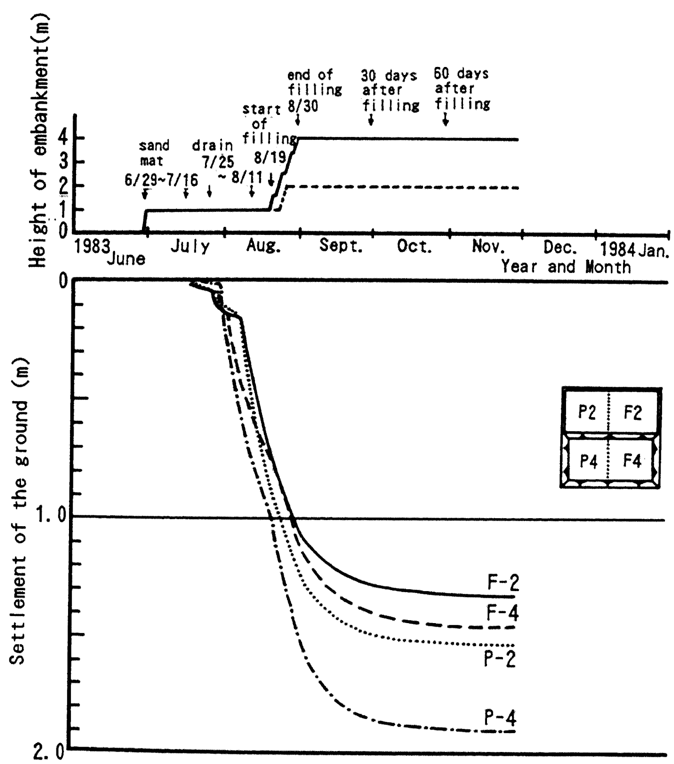

Fig. 11 Time-settlement Curves

Changes of shear strengths due to soil improvements are shown in Fig.13. Closed and open circles are measured shear strengths before improving and 60 days after filling the test embankment, respectively. A solid line shows estimated shear strength at the time of 80 % consolidation. As the open circles are slightly larger than the solid line, it was concluded that shear strength increased up to the necessary level by improving the ground.

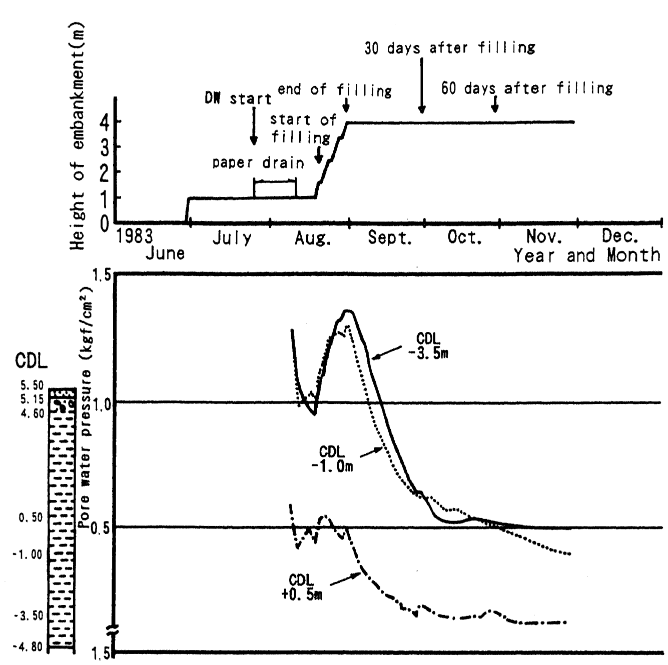

Fig. 12 Change of Pore Water Pressure at Site P4

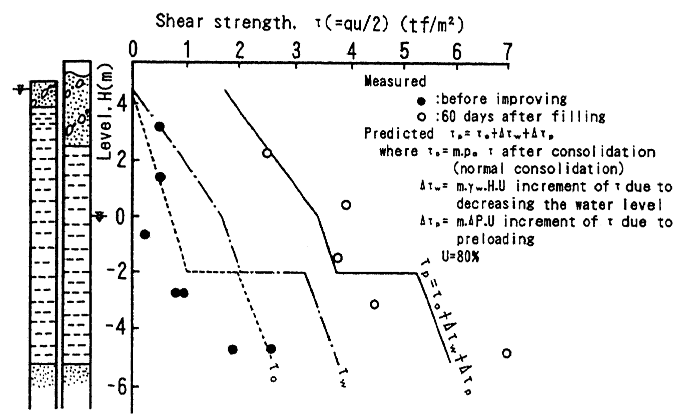

Fig. 13 Change of Shear Strength Due to Decreasing Water Level and Preloading

Fig.14 shows measured groundwater level and head of water in Layer As. The groundwater level decreased up to 4.5 m which was 1.5 m deeper than the design value. Therefore, it was estimated that the overburden pressure increased adequately due to the decrease in the groundwater level. It was estimated also that the installation of deep wells up to Layer Ag had been good design because the head of water in Layer As decreased by more than 5 m.

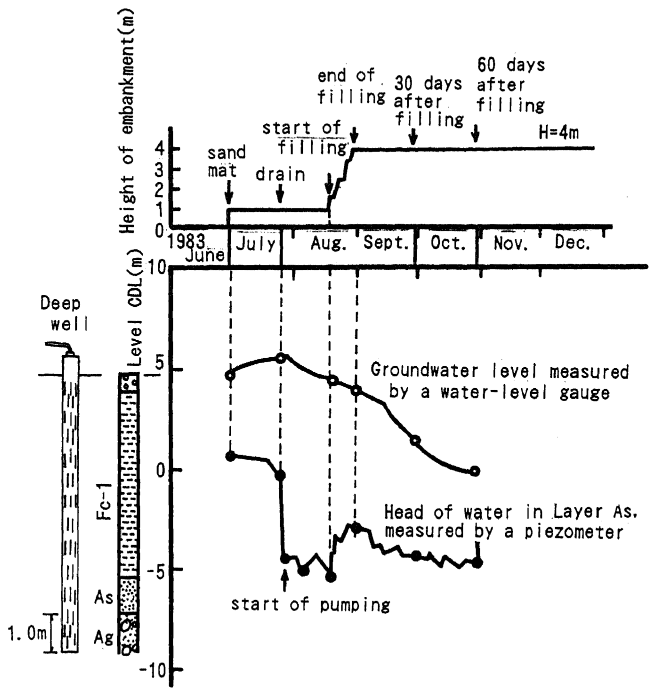

Fig.14 Groundwater Level at Site P4

TEST COMPACTION OF SANDY GROUND

Test compaction by dynamic compaction was carried out inside an area of 25 m x 25 m in sandy ground. Fig.15 shows the soil profile, SPT N-values before and after compaction, and safety factors against liquefaction, F_L, before and after compaction. Closed and open circles in Fig.9 show SPT N-values before and after compaction. As most F_L values in Fig.15 exceeded 1.0 after compaction and the SPT N-values after compaction in Fig.9 exceeded design SPT N-values, the proposed compaction method was judged to be adequate. The design SPT N-values shown in Fig.9 were utilized during the main work also to check the degree of compaction.

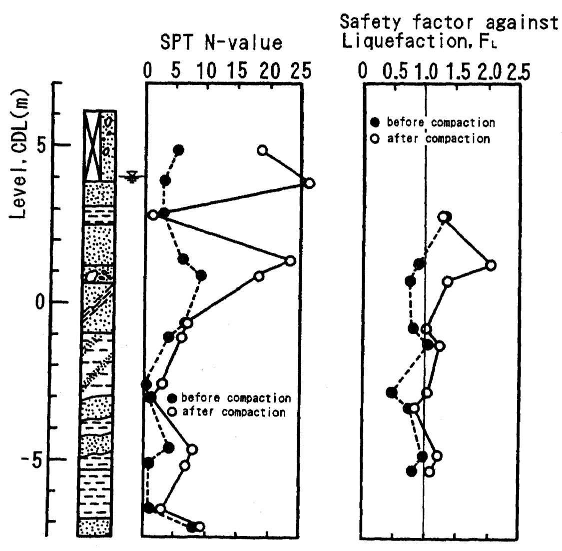

Fig.15 SPT N-values and Safety Factors Against Liquefaction Before and After Compaction at the Test Site

LONG-TERM MEASUREMENT OF SETTLEMENT AFTER IMPROVEMENT

Main work for improvement started in October, 1983 and finished in July 1984. Tomatoh Coal Center was opened in January, 1985. Long-term measurement of settlement was continued until 1988 in the ground supporting the stock embankments of coal, inside the clayey ground. The measured increment of settlement after improvement reached 22 cm. This value was about half the estimated residual settlement, of 43 cm. However, it was noted that careful observation was needed after 1988 because the settlement had increased slightly.

Several earthquakes have hit the yard since the compaction, as summarized in Table 5. Though the estimated peak acceleration during the earthquakes was somewhat less than 80 gals, liquefaction has not been induced in the yard.

Table 4 Major Earthquakes Near the Site

Year	Date	Magnitude M	Epicentral distance(Km)	Estimated acceleration(Gal)
1983	Jan. 4	5.4	87	32
1987	Jan. 14	7.0	90	84
1989	Jan. 25	5.8	95	39
1989	March 30	5.6	187	18
1989	Nov. 2	7.1	321	24

CONCLUDING REMARKS

Tomatoh Coal Center, a coal storage yard for an electric power plant, was constructed on a recently reclaimed land in northern Japan. As the reclaimed soil was very loose or very soft, the ground was improved. Three kinds of improving methods were necessary because sandy soil and clayey soil were distributed non-uniformly. The improvement methods were designed based on many kinds of tests and several analyses. The effectiveness of the improvement methods was checked based on tests in the field. Then, the main work of soil improvement was carried out successfully.

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