GEOTECH-YEAR 2000
Developments in Geotechnical Engineering
27-30 November 2000, Bangkok, Thailand

Development of soil stabilization techniques around the Inland Sea Area, Western Japan - Five decades of experience

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SYNOPSIS Experiences of "failure and success" during the development of soil stabilization techniques in Japan since early in the 1950's up to the present, especially carried out around the Seto Inland Sea area are treated in this paper. Beginning with the first usage of the sand-drain method in Japan in 1951, the first practical application of band-typed drains in the world is introduced. The development of sand compaction piles, deep mixing, jet grouting etc. following the first two methods were also performed in the same area. The last and the latest method introduced and developed in 1996 was fiber drains invented by the National University of Singapore headed by Prof. S.L.Lee, and this method has been highly evaluated and widely accepted in Japan as environment-friendly and sustainable materials, and also retainable themselves to settle the strain of surrounding clays.

1 INTRODUCTION

It was on the eve of an opening ceremony of a newly-constructed fishing port in a village of an island, Hiroshima Prefecture on a winter day of 1951, when many people related to the project came together to celebrate the completion of the harbour. During that evening, when the tide reached its lowest level, the whole structures suddenly sank into the sea bottom, and the next morning, no one could see the jetty or the breakwater there, as if a mirage disappeared. Such an occasion had not been a rare case around the coast of the Inland Sea from ancient times. In constructing a castle on a shore, the stone wall frequently failed and disappeared into the ground. It was believed by the people in the area, that there lived a devil to swallow victims, and usually there needed many times of such victims through successive generations, before setting up the stone wall successfully.

Since the end of the World War II, new sciences and technologies came into Japan, among them soil mechanics and the related technology being included. Needless to mention, the cause of failure of the fishing port was the lack of bearing capacity of the soft ground against the peak load due to the decrease of buoyancy at the lowest tide. And the case of ancient castles meant the soil stabilization by replacement of the foundation soil utilizing artificial base failures and also increase of shearing strength by consolidation of soft clays with the passage of time. Many cases of such foundation failures happened even after the World War II, and the total numbers might reach several tens only in the Inland Sea area, before soil stabilization techniques had been developed and applied widely.

2 THE DAWN OF DEVELOPMENT OF SOIL STABILIZATION TECHNIQUES IN JAPAN

Early in the 1950's, the first trial of soil stabilization techniques had been carried out in Japan.(Takeshita, H. et.al. 1953) In constructing a by-pass way at Kasaoka City, Okayama Prefecture on the Route No.2 from Osaka to Fukuoka, a trunk road of the country, it was planned to pass across a small bay. From preliminary investigations, the average strength of the alluvial clay of more than 10 m in depth, was estimated to be 10 to 20 kP_A. The shearing test result of undisturbed block samples taken from a deep trench showed that c_u = 12 kP_A, and $\alpha_u = 0$. The embankment height was expected to reach 10 m in the central portion of the by-pass road with a short bridge on a narrow canal for fishing boats at the center of the bay. It was clear that an ordinary method of construction at the site would result the base failure of the embankment.

There had not been any experience of soil stabilization techniques among civil engineers in the country in those days, however, there were a brief information concerning sand drains in the U.S.A, which might be a californian experience of the method by O.J.Porter (Porter, O.J. 1936) and a catalog showing a photograph of the installation machine at a certain site, brought back by an earlier visitor to the U.S.A after the War. These documents had attracted attention of engineers in the Hiroshima branch office, the Ministry of Construction and a project of trial usage of sand drains had been started at the site in 1951.

I had just returned to Hiroshima University from Prof. T. Mogami's laboratory, Tokyo University, after about 2 years study on soil mechanics, and began to investigate geotechnical problems at the soil testing laboratory of the above-mentioned office. I was asked to join the project from the beginning, and performed tests on consolidation properties, shearing strength, etc. using undisturbed block samples taken from test pits at the site. I remembered a large-scaled three-dimensional consolidation test conducted in relation to this project, the result (Aboshi, H. 1955) of which had been quoted in an English publication in 1978 (Murray, R.T. 1978) as the first experimental justification on Mandel-Cryer effect. A large model test of sand drains was also performed in the same series of investigation.

Fig. 1 shows a cross-section of the trial embankment with sand drains, 8 m in height. A closed-end pipe pile with a disposable pile tip was used to execute sand drains, and simple manometer-type piezometers were used to measure pore pressure induced in the clay stratum. To avoid air-entraining in pipe lines, a water circulating system was applied before measuring the pore pressure. However, the function of drains or the Barron's theory on sand drains had not yet duly understood among engineers included in the project. Rather, it was misunderstood that the bearing capacity of a soft ground executed with sand drains, which were called sand piles then, was increased by driving these piles to support embankment load, like an ordinary pile foundations.

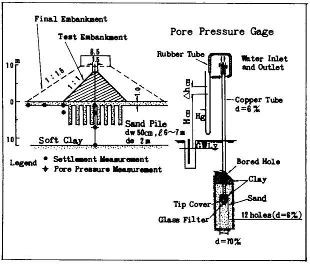


Fig. 1 Trial Embankment with Sand Drain

There was no idea of step loading or a slow rate of loading to expect the increase of shearing strength by consolidation with the passage of time, other than to surcharge embankment load at a stretch. As a natural result, each portion of the trial embankment, with and without sand drains, had failed almost simultaneously at about 5 m in height, which was the ultimate bearing capacity of the original ground. This occasion had given a deep and important instruction to engineers related to the project, that the method could not be a pile foundation to support load, but only to install drains to accelerate consolidation of clay.

One day during the project, I was standing on rip-raps of the embankment crossing the bay and looking over the entire scenery of the project. I felt a slight movement at my feet and heard a low rumbling noise. In another moment, I noticed myself sinking slowly and the movement continuing steadily. I was in a hurry to depart the site, however, it was not such a fast movement which made me feel dangerous in a panic. The road embankment across the bay gradually sank under the sea water and disappeared from my sight, except a small bridge in the center which was supported by caisson foundations.

3 SAND DRAINS, ESTABLISED AS THE FIRST METHOD OF DEEP SOIL STABILIZATION IN JAPAN

One of the earliest big projects in Japan after the War, was the construction of Kojima reclamation embankment, Okayama Prefecture, 8 km in length, closing the Kojima Bay and creating a new rice field of 5200 ha. (S & F 1953) There was no method of soil stabilization when this project was started, and an old countermeasure to such a case, that was to place bundles of brush-wood under the rip-rap as a foundation and to construct wide loading berms on both sides of the embankment. It was necessary to execute the total width of 140 m berms to support the crown width of only 28 m, and 8.5 m in height. It took 12 years period to be completed from 1950 until 1962. However, the stability calculation by slip-circle method was widely understood and became a routine practice among civil engineers through such experiences in the Inland Sea area.(Ishii, Y. 1958) Foundation failures in soft alluvial clays had drastically decreased since then.

During the age of high-growth of economy in the country in the 1960's, it had become a social need to reclaim and fill-up to create new lands along the coast of the Inland Sea, and the establishment of the system to hasten reclamation works had become an urgent necessity. The knowledge on consolidation theory and increase of shearing strength of clays by consolidation had already been understood widely among engineers in those days, and the system to construct enclosing cofferdams in the sea, had been gradually established.

To spread a sand mat on the sea-bed in the first place and to drive sand drains from floating barges at the foundation of reclamation embankments. Next, to surcharge embankment load up to the height of the ultimate bearing capacity of the foundation soil, and to stop and wait until the settlement reaches its 90% consolidation. By taking the increase of shearing strength and also bearing capacity of the foundation soil into account, to place another additional load of embankment until finally reaching the planned height, by repeating the process. These procedure had become a routine work to construct cofferdams for the reclamation.

The development of this system was inevitably accompanied by the progress of field management techniques not only of settlement and pore-pressure measurement, but check boring systems to investigate the effect of soil stabilization. Such a series of techniques to construct the closing cofferdam had quickly been established until about the late 1960's, and only a few years period had become necessitated to complete it, compared with 12 years of construction in the case of Kojima Bay, due to the application of sand drains. The name of sand drain had become familiar not only among civil engineers but even among *entrepreneurs* to use new lands for their need.

The stabilization work of filled-up lands was usually performed after the reclamation finished, according to the needs from structures constructed on the ground, and this procedure had caused another troubles among the users of reclaimed land such as the differential settlement. It took another decade that the whole area of reclamation became executed by sand drains beforehand, the first of such cases being the West Hiroshima Development project, 1971 - 1981, 328 ha in area.(Aboshi, H. 1995 & H.M.G. 1982) The most famous example of this kind of execution of sand drains in recent years was the soil stabilization work of the Kansai International Airport, in which more than a million sand drains of 20 m in length had been driven into the sea-bed of - 20 m.(Arai, Y. 1991)

4 METHOD OF PAPER DRAINS — ITS SUCCESS AND OBSOLESCENCE

It might be an autumn day of 1961, when two gentlemen came to meet me, asking my opinion on the effectiveness of new soil stabilization technique — the card-board drains. It might well be doubted for the two men who were each CEO of a big maker of construction machines and a big contractor, if the idea to stabilize soft grounds by inserting papers into the earth, was an absurd conception. I had not seen the material or the installation machine then, however, I remembered an article of an ASCE journal, in which a discussion between W. Kjellman, the inventor of the method, and R.A.Barron who established the theory of sand drain design, was reported. Barron stated as this, "It is possible that, should wick materials and installation machines become available in the United States, sand well may be outmoded."(Barron, R.A. 1948) So I at once replied them that the method would be reliable and persuaded to introduce it to Japan, deferring to Barron's opinion.

After basic experiments on the drain material and model tests on consolidation properties of it, the two CEO had decided to embark in the development of a new installation machine up to - 20 m deep. There were two huge reclamation projects in Hiroshima for the Mazda Automobile Co.'s main factory and the Nippon Steel Pipe Co.'s new iron mill, one of the biggest iron mills in Japan at that time. In 1963, most of the area of reclamation had been stabilized by utilizing this new method, which was nominated as the paper drain by myself, the total area of stabilization being about 10 million m^2. These two cases were considered to be the first cases of large-scaled utilization of band-typed, prefabricated drains in the world.

This method was widely accepted as a very effective and the most economic method of soil stabilization in those days, and had been executed at more than 200 construction sites during several years since then. However, after numerous field experiences with paper drains until the 1970's, I became aware of the intrinsic defect of the method. During the first trial of the method at Mazda, I had already noticed that the rate of settlement gradually decreased, compared with the theoretical prediction during the later degree of consolidation, in contrast to the larger rate at its earlier stage.(Aboshi, H. et al. 1965)

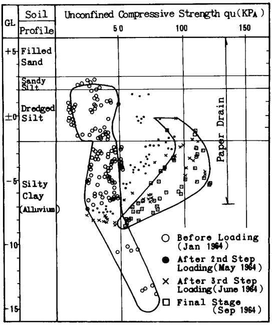


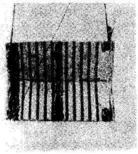
Fig. 2 Increase of Shearing Strength at Mazda

Fig. 2 shows the summary result of shearing strength after consolidation at Mazda. The soil profile of the site consisted of a natural alluvial clay stratum underneath -2 m level, overlaid by a dredged silt of about 4 m in slurry state. About 4 m high reclamation embankment was laid on them. Small white circles in the figure show the initial strength distribution before starting soil stabilization works, and small square points show the final stage of strength distribution. It seemed clear that the strength of the dredged silt stratum had increased by consolidation as was expected, however, those of the natural alluvium underneath the dredged soil had shown a certain retardation of its consolidation process, especially in the deeper part of the stratum.

By observing the deformation of paper drains in both strata after consolidation, I acknowledged the necessity of taking the effect of shrinking deformation of drain itself into consideration, in utilizing band-typed drains. Photographs in Fig. 3 show the deformation of paper drains installed in clay strata. No.1 in Fig. 3 is an inside state of a paper drain material before usage, which clearly shows water drainage striae. No. 2 is a crooked form of a drain taken from the slurry clay stratum after consolidation. Even though it was bent deeply, the inner drainage paths seemed to alive effective. However, shrinking deformation of a paper drain in zig-zag form, surrounded by the consolidated natural clay stratum shown in No. 3 might mean the loss of permeability in vertical direction. The retardation of consolidation shown in Fig. 2 was considered to be caused by such deformation of paper drains.

During the golden age of sand drains, we had frequently experienced insufficient capability of drains, caused by using improper materials such as dirty sand, decomposed granite

No. 1



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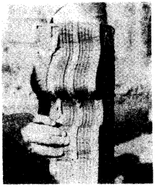

No. 3

Fig. 3 Deformation of Paper Drains

sand, etc. Furthermore, there were many miscarried cases on the usage of sand drains, presumably caused by executing discontinuous drains due to penetration of surrounding slurry clay during driving them. A recent example of such a case observed in a certain huge project in this country is shown in the next figure. Fig. 4 is time-settlement curves of two different points on a closing embankment, the soil properties and surcharging conditions being almost the same, and also the results of check boring on each cases. These data clearly show that even under the advanced system of construction control of today, the discontinuity of drains might be happening .

An instruction drawn from the above experiences is that the flow resistance among drains, and at the same time, among sand mat under the reclaimed land, must be taken into consideration in designing vertical drains, even if the drain material used may seem to be infinitely large in its permeability. (Aboshi, H. & H. Yoshikuni, 1967, Yoshikuni, H. & H. Nakanodo 1974) As for band-typed drains especially those made of plastics, I could not rely on them by the reason that they might not be able to retain the shrinking deformation, especially in case of larger strain consolidation, until I met fiber drains which will be referred later on.

5 SAND COMPACTION PILES – THE METHOD OF COMPOSER

A method of sand compaction piles to densify sand strata was developed in the 1950's in Osaka, Japan. Originally, it was developed as a more economic and rapid compaction method than the vibro-flotation method, developed and introduced from Germany, the method to compact a loose sand stratum horizontally by a vibrating rod. A casing pipe filled with a plug of sand is penetrated into a loose sand stratum by a vibrating rammer at its top, down to the desired depth. After pouring a sandy material in the casing pipe, it is withdrawn part way and driven down again to compact sand column and enlarge its diameter. This procedure is repeated up to the ground surface, forming a compacted sand column and finally compacting the whole loose sand stratum.

This method was extended its application to soft clays in the alluvium. One of the first applications was executed for the foundation of a sea wall at the port of Miyajima, Hiroshima in 1973, about 500 m in length. The replacement ratio of this case was about 70%, and its design concept was a kind of sand replacement method. The sea-wall was successfully completed, except a part of the cross line moved slightly outward. Cosidering that the disturbing effect to the soft clayey ground by installing compacted sand columns might have caused the deformation, investigations of the change of shearing strength of clay surrounding the compacted sand columns with time had been performed. It became clear that once decreased strength had been recovered to the original level by consolidation process in a few months' period after the execution.

The idea to use this method of soil stabilization as a composite foundation, which meant to expect load-supporting capacity of compacted sand columns as piles and at the same time, as sand drains to accelerate consolidation of surrounding clayey grounds, had become to practice in the 1970's. The merit of this concept against ordinary sand drains consisted in the time-saving effect on fill-up works, due to the initial stress concentration on these sand columns. The stress on sand columns measured in the fields was usually 3 to 8 times larger than those on the surrounding clay. Though the cost of construction became somewhat expensive, many of the *entrepreneurs* wanted to choose the shortening of construction period, and as a result, this method had become the most widely used method of soil stabilization in the area until the end of the 1970's, under the brand name of the "composer". (Aboshi, H., Y.Mizuno & M.Kuwabara, 1991) – that meant the composite foundation.

It is a common sense for scientists and engineers in our field, that the strength of clay is reduced by disturbing its structure. So in the earlier days of its development, it was frequently doubted that SCP method might reduce the bearing capacity of soft clays rather than stabilize and strengthen it by disturbing clay structures. Even in its usage as the replacement method, it might fall like dominoes by the existence of slurried clays among compacted sand columns when the horizontal force were applied. However, I myself had never doubted of its effectiveness through many cases of the field experience which always showed its usefulness. Recent model studies by centrifugal apparatus have shown that there might not happen a domino-like failure, which might sometimes happen in small model tests. The SCP method is a typical case that the practice runs first and the theory follows later.

6 DRY JET MIXING (DJM) METHOD

An idea to mix cement or lime with clayey soils in a deep natural stratum in-situ, using a rotating shaft with mixing

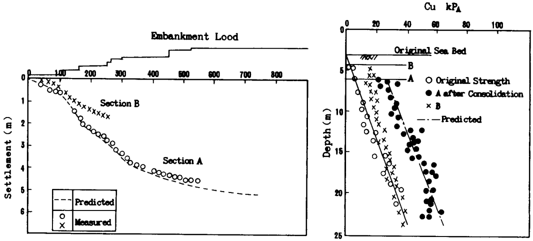

Fig. 4 Retardation of Consolidation due to Discontinuous Drains

blades producing a column of hardened clay-cement or clay-lime in the stratum, was developed to practical usage around the 1970's. The Port and Harbour Research Institute, Ministry of Transport, Japan, had succeeded to develop this method and carried out the first practical usage in 1973. (Okumura, M. et al. 1973) In this case, cement or lime was used as a mixture in a slurry state. This method of stabilization of soft clays has been developed and utilized widely, especially in constructing ports and harbours.

Another similar method in which a slurry material is mixed by a jet-grouting technique, was also developed in the same age. In this method of soil stabilization, the mixing process is carried out by injecting in-situ clay stratum with a high-pressured jet stream containing admixture in a slurry state, from a rotating shaft. (Miki, G. 1973) The above-mentioned two methods use the mixing material, cement or lime, in a slurry state. As soft clay strata usually contain very high water content and needless to mention, it will be better to use admixtures in a dry condition.

A method of DJM was developed in this concept by the Public Work Research Institute, Construction Ministry, Japan and the Research Institute, Japan Construction Mechanization Association, in 1980. (DJM Committee 1990) It was an extremely difficult task to mix dry, powdered cement or lime with clay in-situ in a sufficiently uniform state. Inside of a curved blade attached to a rotating shaft, there appears a narrow space between the blade and the surrounding soil when the blade moves forward. Dry, powdered admixture is poured into this space from holes at the back of the blade, contained in a properly compressed air. After the admixture is sprayed to the surface of clay, the air is recovered at the ground surface through a clearance on the surface of the rotating shaft. (Fig.5) The rotating shaft with this system of powder injection is pulled out slowly, forming a column of clay-dry powdered admixture in the ground. This method of soil stabilization was used in the foundation work of a sewage treatment plant of Kojima Bay area in 1983, being one of the earliest cases of application. It is said that more than 2000 cases of application have already been performed in the country until 1997, and the market share has already reached the top rank among many kind of soil stabilization techniques.

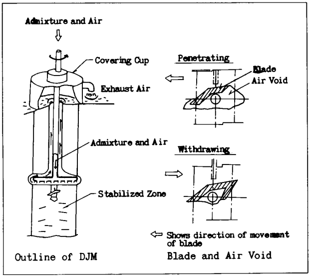

Fig. 5 Detail of DJM

7 FIBER DRAINS

A new band-typed drain was introduced to Japan in the early 1990's. It is made of natural materials only, the cross-section being 90 mm x 9 mm and it consists of four ropes made of twisted coconut fibers, covered by a duplicated jute cloth. Two kind of materials fulfil each other the different part of its capacity, the coconut ropes working as water striae and the jute cloth playing roles of filter and tension supporter. It was developed by the National University of Singapore, headed by Prof. S.L.Lee in the end of the 1970's, for the purpose to replace plastic band-drains which had frequently broken in the execution under strong wind.

I acknowledged the merit of this material at the moment when I saw it, judging from the experience of paper drains. It can be buckled without losing the continuity of water paths in vertical direction, and executed by an ordinary installation machine of band drains, without substantial remodeling. That means there is no need to develop a new machine. The cost of a drain is almost the same as plastic-made one, and totally it is concluded that this method might be able to become a substitute for plastic drains. However, any of governmental officials or contractor's engineers had not paid attention nor appreciated its usefulness mainly because it seemed suspicious to have enough durability as a construction material from its outside appearance.

After investigations on the drain material and the practical test usage in several sites, this method of soil stabilization has been approved for public use in Japan by the Advanced Construction Technology Center, an evaluation organization under the Ministry of Construction in November 1996. There have arisen the public opinion to utilize environment-friendly and sustainable materials almost simultaneously, and it has become a favorable wind for fiber drains. Once a rejected material from the point of durability, has come back to be used by the same reason. Total length of executed fiber drains has amounted 2.2 million meters until present

CONCLUDING REMARKS AND ACKNOWLEDGEMENT

In this paper, I referred mainly to practical experiences on the development of soil stabilization techniques carried out in the Seto Inland Sea area in the last half a century, not on soil mechanics researches in Hiroshima University, where I belonged through my whole career. During these works, I was always worried about the relation between "theory and practice"; as Terzaghi always emphasized its importance in geotechnical engineering. Many times, I have experienced cases in which theory and experimental data in the laboratory could not explain the field practice. One of the most famous examples was a long-continued debate whether sand drains were effective or not, both in Japan and in the USA since the 1970's And the case of sand compaction piles, which is widely used and relied on among practicing engineers, and on the contrary, unpopular among, scientists as a whole.

During my long career as a scientist, I have always been thinking about how the research in geotechnical engineering should be, and what is the most important standpoint in studying it. We scientists usually consider that what is the cause of inconsistency when field data do not coincide with the theoretical prediction. However, there must be a change of conception to think how our model is different from reality in the field, which is the truth. Needless to mention, it does never mean to fit the theory for erroneous data, such as the above-mentioned case of discontinuous sand drains. In this sense, to cultivate the capability to find the truth from confusing reality, is most important.

Now in the age of computers, young men used to stick to their desk works and do not want to see the site. However I would like to emphasize that the truth always exists in the practical phenomenon in the site, and the theory or the experiments in the laboratory should be performed to explain the truth in the field. I strongly hope that the future development of geotechnical engineering will proceed to the right direction.

The corrections and typing of this paper were carried out by Ms Y. Yasunaga, Fukken Co. Ltd., and her assistance is greatly acknowledged.

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