KINKING DEFORMATION OF PVD UNDER CONSOLIDATION OF NATURAL CLAY LAYER

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SYNOPSIS : Almost every material of PVD (Prefabricated Vertical Drain) has the fatal problem on the condition - the length must shorten with the settlement of the surrounding grounds - which all PVDs must satisfy. Kinking deformation by buckling of PVD due to consolidation settlement is discussed in this paper.
A new testing device to clarify the deformation of PVD under consolidation of surrounding clay was developed and the fiber drain and a PVD made of plastics were compared under the same condition of consolidation using natural clay specimens. The results are also shown in this paper.

Key Words : consolidation, deformation of drain, laboratory test, PVD, soil stabilization, vertical drains, kinking

1. INTRODUCTION

Prefabricated vertical drain (abbreviated as PVD) means a vertical drain used to accelerated consolidation of clayey ground which is, in principle, a manufactured product at other than the execution site.
In this meaning, the pack-drain frequently used in Japan since the earlier period of soil stabilization works, is not PVD, because the formation of the drain, that is only a simple operation to fill sand into a stocking-like long sack, is usually performed in-situ.
Invention of the first PVD was done by Dr. W. Kjellman, the director of Swedish Geotechnical Institute then, in 1937. It was made of a paper material and called as Card-Board Drain. A trial machine to install this PVD of 5 meters in length had been manufactured, and used in a test field, however the further development of this method was sealed, owing to a trouble on the patent right.
In the early 1960's, this method was introduced in Japan. By manufacturing a new type of machine, capable of executing a drain of 26 meters in length, the first practical usage of PVD in the world was performed in Hiroshima. (Aboshi,H et al., 1965)
Paper drains, named by the first author in those days, were executed to stabilize a total of 10 million m2 of newly reclaimed lands for the Mazda Automobile Co.'s and the Nippon Kokan Co.'s main

factories in 1963.

In the 1970's, O. Wager of SGI developed a PVD made of plastics. It consisted of a core of polyethyllene plate, surrounded by a hard kraft paper, and was called Geodrain. This became the model of another PVD made of plastics, developed afterwards. The differences of plastic PVD were on the shape of cross section of plastic core, and the filter materials.

As for the core, these are many minor differences, the cross-section as shown in Table 1. The plastic material used is almost made of a thin hard polyethylene, and the appearance of this material had made possible to produce plastic PVDs, by its durability and ductility.

On the other hand, the filter material was usually non-woven fabrics or fine stitched cloths, and sometimes paper materials like the Geo-drain.

The first author had acknowledged the fatal defect of PVD, through his experience on the usage of paper drains at over 200 construction sites in the 1960's.

According to a result of check boring after consolidation at Mazda, it is clearly shown that paper drains were effective in soft dredged silt layer, but unsatisfactory in the natural alluvium of silty clay.

Comparing to the classic sand drains, every one may notice that any vertical drains must shorten its length during consolidation that means to shorten the layer thickness of surrounding clay. Sand columns can shorten their length without any difficulty, shorten the length and widen the diameter slightly without loosing the vertical continuity and permeability.

The PVD must bend, or in any shape, must move laterally, during consolidation process, and here lies the intrinsic defect. It may be expected to move laterally in order to bend itself, but it is easily calculated as shown in the following section that it is impossible to move laterally in natural clay layers.

Fibre drains developed by NUS, headed by Prof. S. L. Lee, in the 1980's, is PVD of another category. It consists of natural fiber materials, which have enough durability during soil stabilization works, and after that duration it is eroded to become the earth. However, the most important point to estimate this PVD is, like sand drains, it can be shortened its length without moving laterally, or bending, by only increasing its thickness.

2. STRUCTURE OF PVD

A PVD including plastic board drains and fiber drain can be defined as any prefablicated material or product consisting of synthetic or natural filter jacket surrounding a plastic or a natural core having the following characteristics.

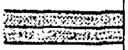
Ability to permit porewater in the soil to permeate into the drain

Ability to permit to permeated porewater to drain away outside of the ground

c) Strength, mainly of tensile, to bear the process of execution in-situ.

The jacket material of PVD consists of non woven polyester or polypropylene geotextiles, synthetic paper, or vegetable fiber that function as physical barrier separating the flow groove from surrounding soft clay soils and a filter to limit the passage of fine particles into the core. The plastic or fiber core serve two vital functions, in other words, to support the filter jacket and to provide flow paths along the drain even at large lateral pressure. The structure of typical PVD products are shown in Table 1.

Table 1. Shape and material of PVDs

Name	Schematic Diagram	Structure	Material
PVC Drain		Porous-sole	Vinyl chloride Resin
Chemical Board Drain		Complex	Filter: Non-woven Textile Core : Vinyl chloride Resin
Castle Board Drain		Complex	Filter: Non-woven Textile Core : Polymorephin Resin
Tafnel Drain		Homo-geneous	Non-woven Textile
OV Drain		Complex	Non-woven Textile
Geo Drain		Complex-separation	Filter: Non-woven Textile Core : Polymorephin Resin
Mebra Drain		Complex-separation	Filter: Non-woven Textile Core : Polyethylene Resin
Ali Drain		Complex-separation	Filter: Non-woven Textile Core : Polyethylene Resin
Colbond Drain		Complex-separation	Filter: Non-woven Textile Core : Polyethylene Resin
Fibre Drain		Complex	Filter: Woven hemp Core : Coconut fiber Rope

3. THEORITICAL APPROACH ON KINKING DEFORMATION OF PVD IN CLAY LAYER

Fig.1 a) shows a PVD executed in a natural clay layer. When the layer thickness is reduced by consolidation, the length of PVD must be reduced at the same time. As it is usually impossible for PVD to shrink itself with the surrounding clay, it is compelled to move laterally by bending. A horizontal force is generated on the surface of the PVD as the reaction.

Fig.1. Lateral movement of PVD

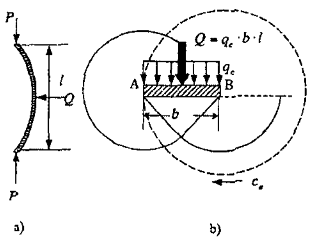


Fig.1 b) shows a horizontal cross-section at the center of PVD. The earth pressure on both sides of PVD is always balanced, and in order to move this PVD laterally in the clay layer, the above Q must be in excess of the bearing capacity of the clay layer in horizontal direction. The reaction by bending of PVD can not at all exceed such bearing capacity, except the case of slurry state mud.
In conclusion, the shrinking deformation of PVD becomes the same problem with the buckling of a column on elastic foundation shown in Fig.2.
The solution of this equation is shown as follows.

$$Pcr = 2\sqrt{\beta EI} \qquad (1)$$

where, is the buckling load, in case when l is large enough (JSCE, 1986).
And the most important point is the half wavelength of sinusoidal buckling curve shown as follows.

$$l / n = \pi \sqrt[4]{\frac{EI}{\beta}} \qquad (2)$$

l / n : half wave length, EI : rigidity of PVD
β : elastic modulus of surrounding clay ground
Determination of EI is performed by a simple beam test shown in Fig. 3.
Finally, buckling load and half wave length are expressed by

$$Pcr = 2\sqrt{\beta EI} = \sqrt{\frac{P\lambda^3 E_{50}}{12\delta}} \qquad (3)$$

$$l / n = \pi \sqrt[4]{\frac{EI}{\beta}} = \pi \sqrt[4]{\frac{P l^3}{48\delta E_{50}}} \qquad (4)$$

It must be stressed here that Pcr and l / n of PVD are directly affected by β or E_{50} of the surrounding clay, and it is inevitable to use an undisturbed clay specimen to examine the deformation properties of PVD in-situ, rather than a slurry clay frequently used in such tests.
The practical value of Pcr and l / n in equations (1) and (2) were determined for a PVD made of plastics as follows.

Pcr = 689 N, l / n = 2.64 cm.
Where, λ = 20 cm, P = 0.733 N, δ = 0.5 cm, E_{50} = 490, N/cm^2, EI = 244.4 $N \cdot cm^2$.
On the other hand, EI of Fibredrain is very small and l / n for it is practically null.

Fig.2. Column on elastic foundation

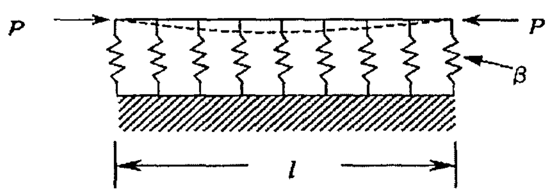
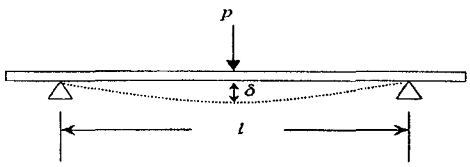


Fig.3. Simple beam test to determine *EI* of PVD



4. CONSOLIDATION TEST RESULTS OF NATUARAL CLAY WITH PVD

Two series of tests were conducted using samples from different sites (Aboshi H. et al., 2001). Undisturbed samples of the first case of the test were taken in the city center of Hiroshima. Sampling depth was -15 m, taken from an alluvial marine clay layer. The second samples were taken from a shallower depth at the coast of Kojima Bay, Okayama Prefecture. Physical properties of both samples are tabulated in Table 2.

Table 2. Physical properties of two cases

		Case	
		I	II
Depth		-15m	±0m
Grain size	Sand (%)	20	5
	Slit (%)	62	47
	Clay (%)	18	48
Natural water content w (%)		41	52
Liquid limit w_L(%)		49	64
Plastic limit w_p(%)		21	22
Plasticity index *PI*		28	42
Compression index C_c		0.36	0.53
Consolidation yield stress $\acute{o}_c$ (kN/m2)		300	78
Average E50 (N/cm^2)		490	

Consolidation properties of two half-cylindrical undisturbed clay specimens, a plastic made PVD and a Fibredrain being inserted in each ones, are compared under the same step loading. Three numbers of pressure transducers to measure the pore water pressure were installed at the bottom of the specimen.

Fig.4 is an example of pore water pressure change during consolidation test. This diagram shows the pore water pressure change measured by transducers during the two steps of consolidation when = 785 kN/m^2 and 1422 kN/m^2. For the case of FD material, the pore pressure converged to zero at the time of EOP consolidation. In contrast to the case of FD material, in the case of PD material, it was found that approximately 5 m water head remained at the pore pressure transducer, although the clay specimen was under the secondary compression stage.

The final settlement strain in this test was ξ_{ζ} = 24% for FD material and ξ_{ζ} = 19% for PD material. After finishing the test, the surcharge was unloaded, and the permeability of both drains in their final state was measured directly by flowing water in PVD. The coefficient of permeability k in FD was in the order of 7×10^{-7} cm/s, however in case of PD, no permeability at the end of the test.

The deformation of drain materials after the end of consolidation testing was compared. The FD material was shortened and the lateral deformation was hardly observed. But instead, its thickness got bigger from approximately 9mm to 10~12mm. On the other hand, the PD material was crooked at three or four spots, instead of sinusoidal buckling of short wave length, as was expected from the theory. The photograph is shown in Fig.7. It is speculated that once a small crook happens at a certain portion, the strain around it becomes concentrated to the crook, causing deep crooks at a certain interval on PVD. These crooks caused the occurrence of residual pore water pressure and no permeability at the end of the test.

Fig.4. Pore water pressure versus time curve

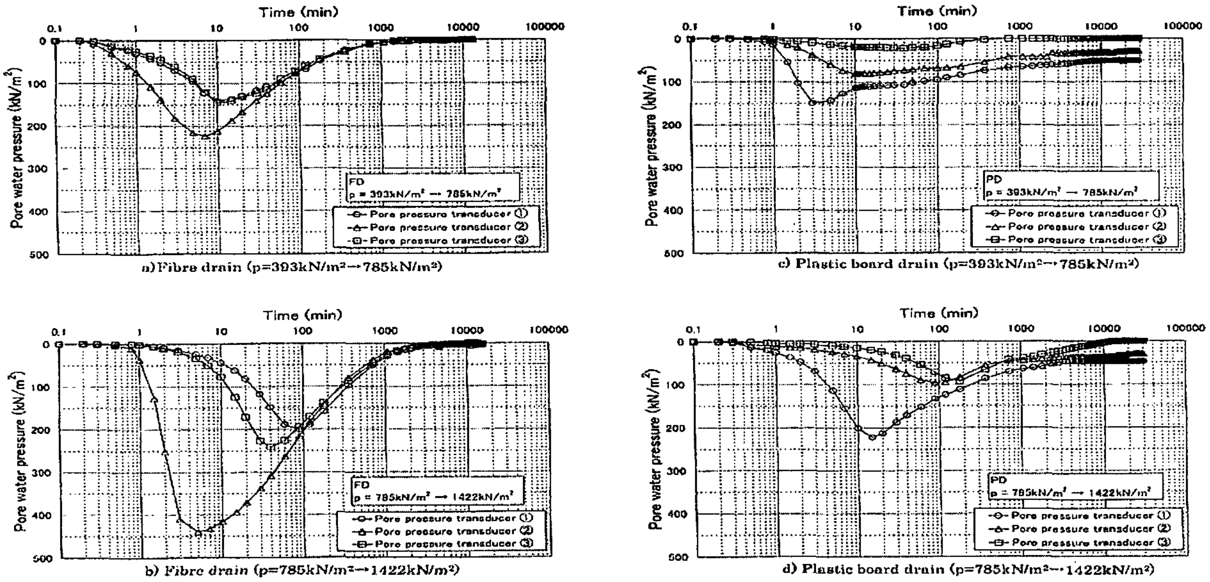
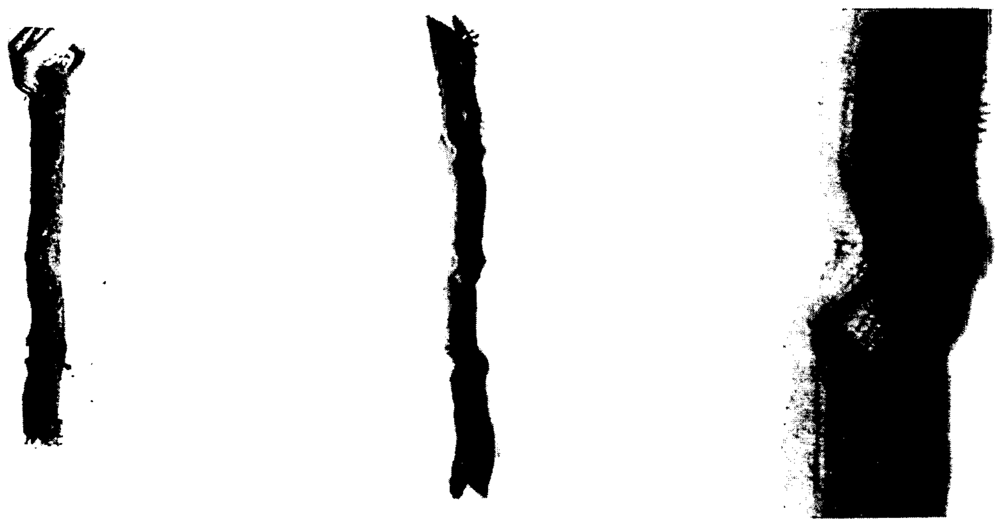


Fig.5. Photograph of PVD deformation after consolidation



a) Fibredrain　　b) Plastic board drain　　c) Plastic board drain (Enlarged)

5. FIELD PERFORMANCE OF PVD METHOD

The comparison of the actual field performance of PVD, between PD and FD, have been practiced in Japan. Fig.6 and 7 show the one of those case studies which shows the monitoring result of consolidation settlement of clay layer improved by PD and FD.

It seems that permeability of PD is disappear due to kinking phenomenon before the end of consolidation. Therefore it is speculated that some residual porewater pressure is still remaining in the clay layer improved by PD, as a result, might increase its residual settlement. On the contrary consolidation settlement of clay layer improved by FD is still continuing after computed EOP settlement due to secondary consolidation.

Fig.6. Comparison of computed and measured settlement, stabilized by SD and FD
(Ujina Port, Hiroshima, Japan)

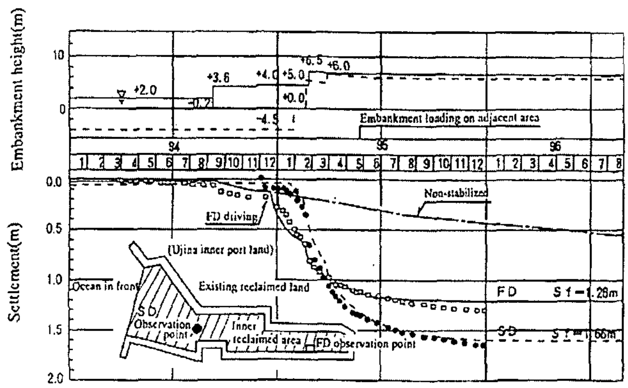
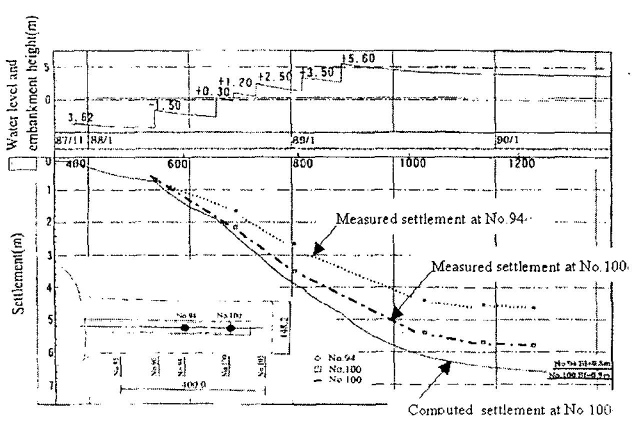


Fig.7. Comparison of computed and measured settlement, stabilized by PD
(Extension Project at Izumo Airport, Lake Shinji, Japan)



6. CONCLUSIONS

Conclusions of this paper is summarized as follows.

1) From theoretical analysis, assuming the shrinking deformation of a PVD as the buckling of a column on an elastic foundation, it is found that the half-wave length of sinusoidal buckling curve of commonly-used PVD made of plastics, is only 2 or 3 cm order.
2) PVD can not be bent deep in a natural clay layer during consolidation of the layer, even in case of very soft clays.
3) Sand drains can deform laterally without losing vertical continuity under consolidation and as a result, can sustain their function as drains even in larger strain. However PD cannot shrink themselves and crook or kink at certain intervals by buckling, losing their vertical permeability in larger strain deformation. There must be a certain limitation of usage in term of consolidation strain for each PD.
4) Fibredrain has an intermediate nature between SD and PD, without any kinking deformation and is still alive as drain until at least 24% strain.
5) Field measurement example of consolidation settlement of clay layer, improved by FD and PD, are shown in the last chapter. It seems that it shows the same characteristics as the above-mentioned.

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