

The Mobilized Strength of Prefabricated Vertical Drains

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ABSTRACT: This paper focuses on the mobilized strength of prefabricated vertical drains, or PVDs, and is based on the results of theoretical, laboratory and field testing on prototype PVDs. Used herein are PVD simulated units known as load-elongation measuring strips, or LEMS. Results of the paper show that the typical strength of commercially available PVDs are well in excess of the required strength when installed by properly functioning construction equipment.

KEYWORDS: Drainage, Wick Drains, Tensile Strength and Survivability

1 INTRODUCTION

PVDs have replaced conventional sand drains over the past 20 years, by providing an economical solution to rapidly consolidate fine grained saturated soils. When building on such compressible soils, large settlements are anticipated. As the soil cannot compress at a greater rate than release of the excess pore water pressure, such settlement can continue for a long period of time. PVDs are used to expedite this release of pore water hence they decrease the time for settlement and greatly facilitate the stabilization of such sites.

PVDs are approximately 100 mm wide by 2 to 5 mm thick. They are delivered on site in large rolls. Most PVDs consist of a synthetic drainage core surrounded by a nonwoven heat bonded or mechanically bonded geotextile filter. They are installed vertically in the ground by a pile driving type of construction equipment known as a "wick sticker". Spacings are typically at 1 to 5 m throughout the soil to be stabilized. The length of the drains are site specific but usually extend to the bottom of the soft soil involved.

Once the PVDs are installed over a large area, a surcharge load is placed on the ground surface to mobilize excess pore water pressure in the foundation soil. The expulsion of the water is coincident with consolidation of the soil resulting in settlement at the ground surface. Additional surcharge load is placed in incremental lifts in accordance with the design requirements. The duration of the load depends on the soil characteristics, PVD spacing and type of PVD utilized.

There is a wealth of information available on the technique and a tremendous number of PVDs have been successfully installed around the world. The design method for determining the consolidation time versus PVD spacing as well as the required flow rate has been fully described in the literature. For example, Hansbo [1979]

has developed the relationship usually used to determine the PVD spacing as a function of the desired consolidation time. Holtz, et al. [1991] has given guidance on the flow rate capacity of PVDs in the unkinked and kinked conditions.

Conversely, the mechanical strength requirements of PVDs has seen little quantitative analysis and discussion. The only reference, Kremer, et al. [1983], reports the need for a PVD tensile strength of 500 N at a corresponding minimum strain of 2%. They also suggest a maximum strain of 10%. This upper strain limit is imposed in order to avoid unwanted deformations that might compromise the drain's dimensions and thus flow capacity. The technical background for these tensile strength and strain values is not known. Thus, the pursuit of a more rigorous numerical and experimental treatment of the tensile strength requirements during installation of PVDs is the purpose of this paper.

The tensile strength of PVDs is a consideration both during installation and during consolidation. Installation challenges the drain's strength as it threads through rollers of the wick sticker. The strength of the PVD is also challenged during the mandrel withdrawal process. Both of these situations are exacerbated by high installation speeds. In addition, the tensile strength may also be an issue when the drains are collectively used to resist a circular arc failure of the weak, sensitive soil. A large number of PVDs "sewn into the ground" and working as a unit will intercept and resist such a circular arc failure. This, however, is a design issue and is not addressed in this paper.

The paper will describe theoretical, laboratory and field research aimed at determining the mobilized strength of PVDs. The paper will conclude with generic recommendations on the required strength of PVDs based on the results of this investigation.

2 INSTALLATION

Typical equipment used to install PVDs is shown in Figure 1. Lighter trackhoe mounted units are sometimes used when the PVDs are relatively short, e.g., less than 15 m deep. Collectively, we will refer to all PVD installation equipment as "wick stickers". Wick stickers contain a mandrel which encases and carries the PVD while it is being driven. Mandrel designs are product specific. Rhombic mandrels with tapered ends are often used for high speed driving in soft soils. T-shaped mandrels reinforced with a longitudinal steel fin and fitted with harden steel driving tips are used when hard surface layers need to be penetrated. Mandrels are designed to minimize disturbance of the ground and to reduce smear and remolding of the soil adjacent to the PVD.

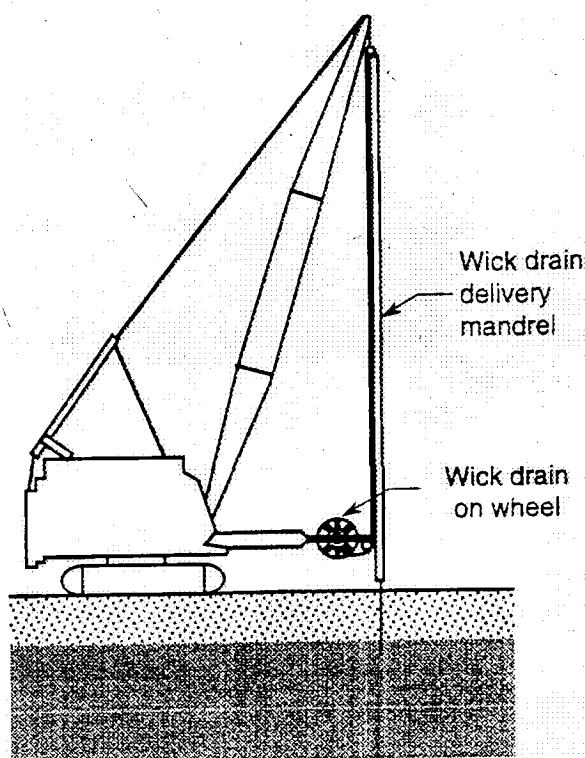


Figure 1. PVD installation rig, a wick sticker.

At the bottom of the mandrel the PVD is fixed to an end assembly that remains in the ground as the mandrel is withdrawn. The purpose of the end assembly is to keep the PVD fixed at the bottom of the soil layer while at the same time keeping soft soil from entering the mandrel as it is driven.

3 THEORETICAL CONSIDERATIONS

PVDs strengths are challenged during installation partly from the drain's self weight and partly from friction between the drain and various parts of the installation equipment. Worst case scenarios are envisioned as maximum forces are developed in the PVD when the mandrel accelerates from a full stop to full speed. Four limiting conditions are identified. These conditions are when the drain is pulled from the roll, as the drain passes through the conveyance system and under the lower roller, as the drain passes over the fixed cylindrical guide roller at the top of the rig, and when the mandrel is retrieved from the penetrated soil leaving the PVD in place.

The first condition investigated is when the drain is initially pulled off the roll. This is a process where the drain is drawn into the mandrel of the installation equipment. This incremental rather than continuous process requires the use of peak rather than average speed for the calculations. By using an angular acceleration of the roll with peak velocity of the wick sticker, a required force of only 14 N is mobilized in the PVD. This occurs at the beginning of each drive when there is a full roll of drain on the reel. The situation is analytically suggested to be as follows:

Velocity of Roll

$$V_{ave} = \frac{L}{D} = \frac{18m}{18sec}$$

$$V_{ave} = 1m / sec$$

$$2\left(\frac{1}{2}(1)V_{peak}\right) + 16 \text{ 1/peak} = 18$$

$$V_{peak} = 1.06m / sec$$

Acceleration of PVD Roll

$$a = \frac{V_{peak}}{t} = \frac{1.06m / sec}{1sec} = 1.06m / sec^2$$

$$\alpha = \frac{a}{r} = \frac{1.06}{0.6} = 1.77 \frac{rad}{sec^2}$$

Center of Gravity of PVD Roll

$$k^2 = \gamma^2 + r^2$$

$$k = \sqrt{(1)^2 + .6^2}$$

$$k = 0.61m$$

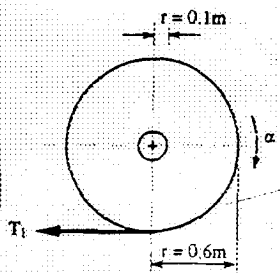
$$mass_{max} = m = 25kg$$

$$\Sigma M_o = I\alpha$$

$$T_1(0.6) = \frac{1}{2}mk^2\alpha$$

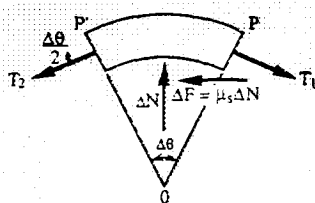
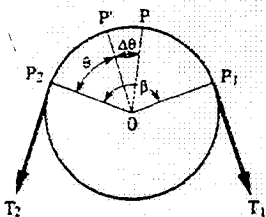
$$T_1 = \frac{1}{0.6} \left[\frac{1}{2}(25)(0.61)^2(1.77) \right]$$

$$T_1 = 13.6 \text{ N}$$



Note, this is the maximum force due to the fact that m and α decrease as the drain is utilized off of the roll.

In the second condition, the drain passes through the conveyance system and under the lower roller. There exists a relationship between the tension in the drain before it enters and after it leaves the roller. This relationship is based on the assumption that the drain is just about to slide into motion. By taking a free body diagram of a small element of the drain the forces acting on the drain are the two forces of tension, the normal component of the reaction of the roller and the friction force. A relationship is obtained knowing that motion is imminent by letting the angular change of the drain approach zero. As seen in the following calculations, only 25 N of strength is required of the PVD in such a condition.



$$\Sigma F_x = 0: (T + \Delta T) \cos \frac{\Delta\theta}{2} - T \cos \frac{\Delta\theta}{2} - \mu_s \Delta N = 0 \quad (1)$$

$$\Sigma F_y = 0: \Delta N - (T + \Delta T) \sin \frac{\Delta\theta}{2} - T \sin \frac{\Delta\theta}{2} = 0 \quad (2)$$

Solving Eq. 2 for ΔN and substituting Eq. 1

$$\Delta T \cos \frac{\Delta\theta}{2} - \mu_s (2T + \Delta T) \sin \frac{\Delta\theta}{2} = 0$$

Divide by $\Delta\theta$

$$\frac{\Delta T}{\Delta\theta} \cos \frac{\Delta\theta}{2} - \mu_s \left(T + \frac{\Delta T}{2} \right) \frac{\sin(\Delta\theta/2)}{\Delta\theta/2} = 0$$

Let $\Delta\theta$ approach zero

$$\frac{dT}{d\theta} = \mu_s T = 0 \quad \frac{dT}{T} = \mu_s d\theta$$

By integration

$$\ln \frac{T_2}{T_1} = \mu_s \beta \quad \text{or} \quad \frac{T_2}{T_1} = e^{\mu_s \beta}$$

Given

$$\beta = \pi \text{ rad, and}$$

$$\mu_s = 0.2$$

Since:

$$F = T_1 = 13.6 \text{ N}$$

Therefore the PVD experiences the following after it exits the lower roller

$$T_2 = e^{\mu_s \beta} T_1$$

$$T_2 = e^{(.2)(3.14)}(13.6)$$

$$T_2 = 25 \text{ N}$$

In the third condition, the PVD is considered to be sliding over the roller at the top of the rig. The tensile force in the PVD is calculated by assuming geometric and frictional characteristics of an upper roller for typical construction equipment. The calculations are similar to that of the lower roller. Liberties were taken in estimating the frictional characteristic of the roller. Conservative values were chosen assuming that the roller would seize-up and become partially fixed. Regardless of these conservative assumptions, a relatively low force of 47 N was mobilized in the PVD for this condition.

Upper Roller

$$T_3 = e^{\mu_s \beta} T_2$$

$$T_3 = e^{(.2)(3.14)}(25)$$

$$T_3 = 47 \text{ N}$$

The fourth condition is when the mandrel is withdrawn and pulled out of the soil leaving behind the drain and its end assembly. As stated previously, the end assembly anchors the PVD and keeps soft soil out of the mandrel. It is possible, however, that some soil can enter the bottom of the mandrel. This in turn will impede release of the drain and subject it to a tensile force by snagging the PVD at the tip of the mandrel. Assuming such a condition exists, the end assembly constitutes the resisting force, where the

friction caused by the soil in the end of the mandrel constitutes the driving force. The calculation and assumptions associated with this condition follows. This worst case scenario results in a mobilized strength of approximately 103 N in the PVD.

3.1 Friction in the Mandrel

Using Mohr-Coulomb criteria

$$\tau = \sigma_n \tan \phi + c$$

$$\tau = c \text{ assuming } \phi = 0$$

$$\tau = c = 10,000 \text{ Pa for typical soft clay}$$

$$\Sigma F_y = T_4 - 2\tau e A = 0$$

$$T_4 = 2\tau e A$$

$$T_4 = 2(10,000)(30\%)(.1)$$

$$T_4 = 600 \text{ N}$$

However can such a force be mobilized in the drain?

3.2 Bearing Capacity of End Rod

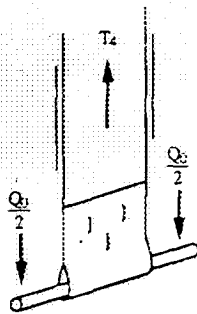
$$Q_o = Q_p + Q_s$$

$$Q_o = A_p p_o + 0$$

$$Q_o = A_p (cN_c + 9N_a)$$

$$Q_o = .002(10,000)(5.14)$$

$$Q_o = 103 \text{ N}$$



Since $Q_o \ll T_4$, T_4 will never be mobilized and therefore Q_o governs

4 LABORATORY INVESTIGATION

The purpose of the laboratory investigation was twofold; to verify, or refute, the theoretical values just calculated (wherein many assumptions were required) and to develop a means of determining the mobilized strength of PVDs in the field. To aid us in these pursuits, we constructed a laboratory wick sticker simulator. A schematic diagram of the laboratory wick sticker simulator is shown in Figure 2. The simulator was constructed in the high bay region of GRI's soils laboratory. The high bay allowed for an upper fixed roller height of 10 m above the floor level.

By positioning a load cell at different locations along the PVD path, one could check the mobilized strength of the drain along the path. Results from this exercise showed that the first, second and third conditions resulted in average load cell responses of 10 N, 18 N and 150 N

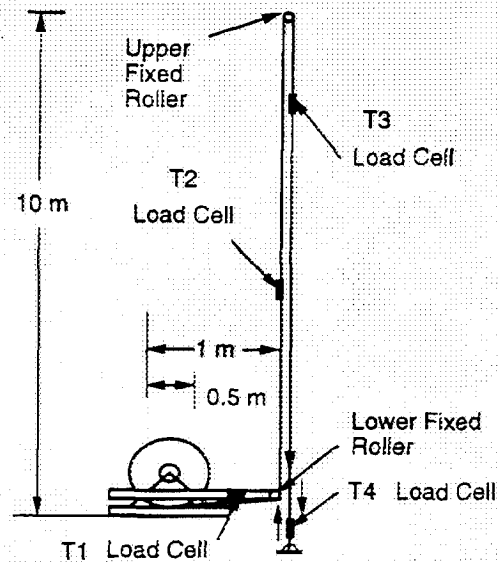


Figure 2 Schematic of laboratory wick sticker simulator.

respectively. To simulate the fourth condition we had to make up a model in the soils lab of an end assembly attached to a PVD being pulled from a freshly remolded column of soft soil. The PVD experienced widely different loads in this simulation depending on the amount of friction imparted in the mock mandrel. Loads in the PVD varied from 25 to 250 N.

These laboratory simulations were interesting, however, it was clear that we could not use the load cell out in the field. It was too cumbersome and fragile to withstand the rigors of field work. Hence we set out on developing a means of determining the mobilized strength of PVDs remotely. Six different techniques were attempted to measure the load elongation response of the PVD. They included:

- Foil strain gages similar to those used by Risseuw [1986] and Guglielmetti, et al. [1996]
- Load sensitive film which changes color upon being stressed to different levels
- Spray applied coatings which crack to varying degrees after being stressed
- Hole punching to reduce PVD strength
- Side cutting PVD to incrementally reduce its strength
- Development of a simulated PVD unit called "Load-Elongation Measuring Strip" (LEMS)

Of all the techniques attempted, the LEMS showed the most promise. This specially prepared PVD consisting of a polyamide (3 x 3) grid fabric as a core, heat bonded between two 160 g/sq. m. nonwoven PET geotextiles. At 2 m intervals along the LEMS, the geotextile was cut away and specific number of polyamide yarns were cut. This left known numbers of yarns intact which allowed the LEMS to

model progressively weaker PVDs. This procedure was used to develop the curves shown in Figure 3. From this data an average breaking strength of 78 N per yarn was obtained. For comparison purposes, Figure 4 shows the tensile strength behavior of commercially available PVDs. For all tests of Figure 3 and 4 the gage separation was maintained at 100 mm and the strain rate was 10 mm/min.

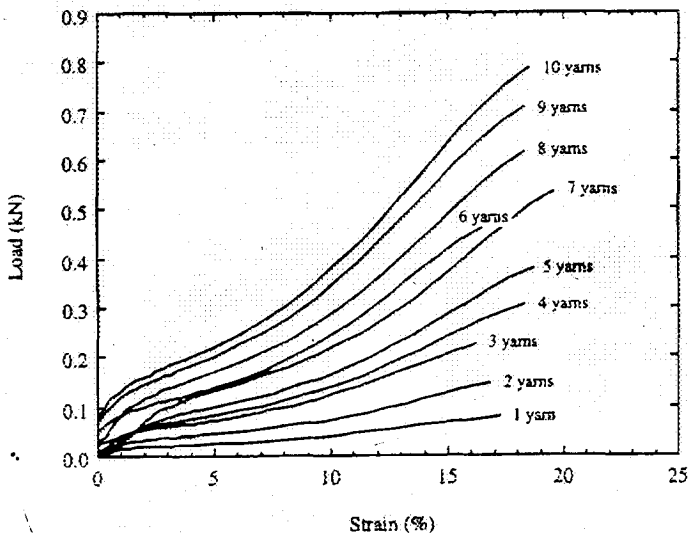


Figure 3 Load elongation behavior of LEMS.

With the LEMS now calibrated insofar as its strength per yarn is considered, laboratory trials on the wick sticker simulator were undertaken. In conducting these trials friction in the rolls was increased using a brake and weight assembly to sequentially cause failure of the LEMS. The results of approximately 27 trial runs (with different numbers of uncut yarns) provided the results of Figure 5. The trend is linear resulting in a slope of 75 N per yarn. This roughly agrees with the tension testing in the constant rate of extension machine as noted previously. Equipped with this confirmation, we took the LEMS to the field to try and verify our theoretical and laboratory findings.

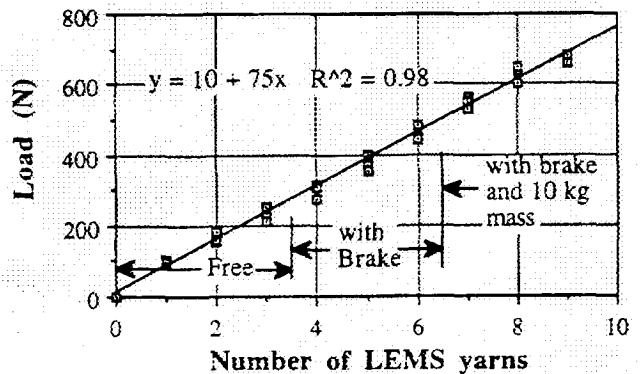


Figure 5 Results of LEMS calibration on simulator.

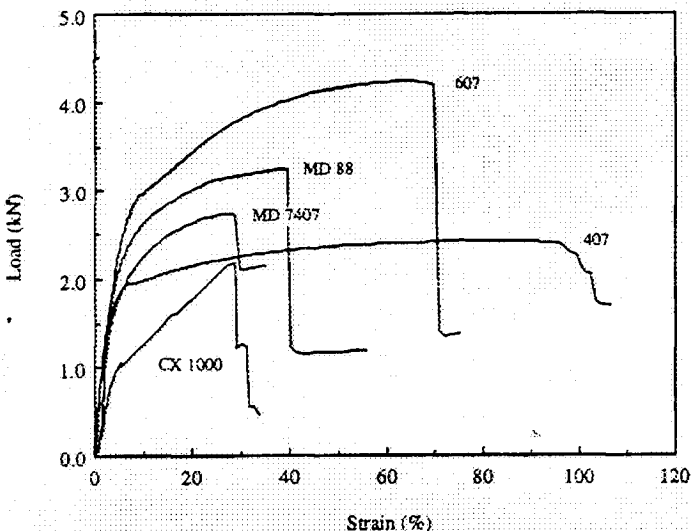


Figure 4 Commercially available PVD load elongation responses.

5 FIELD INVESTIGATION

Field trials with the LEMS material were conducted at a major soft soil stabilization project at the Philadelphia International Airport. Through the cooperation of Day & Zimmerman Infrastructure, Inc. and Geotechnics America, Inc. (the PVD contractor) a field trial of the LEMS was conducted in October of 1997.

As reported by Koerner [1997], the results of the field work are summarized in Table 1.

Table 1 - Field Behavior of LEMS at the Philadelphia International Airport.

No. of Yarns in LEMS	Resulting Strength of LEMS (N)	No. of Repeat Trials	Result of Each Trial
20	1540 N	2	pass/pass
14	1080 N	2	pass/pass
10	770 N	3	pass/pass/pass
5	390 N	3	pass/pass/pass
3	230 N	2	fail/fail

The results of Table 1 indicate that the mobilized PVD strength for this particular construction equipment and site condition is between 390 and 230 N. It must be clearly stated that it is believed that site conditions and

construction equipment will influence results. However, these limited results are insightful none-the-less.

6 SUMMARY AND CONCLUSION

It appears from theoretical calculation, laboratory testing and a limited field investigation that the strength of most commercially available PVDs are greater than required for installation. In addition, it appears that the current trend of increasing the strength requirements of PVDs is unfounded. At present, there does not appear to be any tangible reason for increasing PVD strengths over and above those that are currently being manufactured. For example, Figure 4 indicates that available PVD tensile strengths are from 2000 to 4000 N. Most commercially available PVDs meet or exceed equipment imposed installation stresses as demonstrated in this paper.

In light of the low values of mobilized PVD strengths developed in this study, e.g.,

- theoretically: 14 to 103 N
- experimentally: 10 to 250 N
- field: 230 to 390 N

we are confident in stating that there is an inherent factor of safety for most commercially available PVDs. Of all installation conditions described, it appears that withdrawal of the mandrel is the governing strength condition. Loads during withdrawal of the mandrel are site specific. They depend on the type of anchor plate and will only take place at the tip of the PVD where it connects with the end assembly.

The requirement for discharge of water at this location is limited since it is at the end of the drain. The load in the rest of the drain is probably less than 230 - 390 N. It is interesting to note that this corresponds with an elongation of approximately 2-4% for most PVD.

It is concluded that all commercially available drains have strengths and elongations at break which are much higher than necessary. Hence, the available factors of safety for mobilized strength is in the range of 4 to 11. We question if the higher factors of safety are warranted in the event that ones construction equipment is functioning properly and geometrically equipped to drive the specific PVD delivered to the specific job site.

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REFERENCES

- Guglielmetti, J. L., Koerner, G. R. and Battino, F. S. (1996), "Geotextile Reinforcement of Soft Landfill Process Sludge to Facilitate Final Closure: An Instrumented Case Study," Proceedings of GRI-9 Conference on Geosynthetics in Infrastructure, Enhancement and Remediation," R. M. Koerner and G. R. Koerner, Eds., GII Publ., Philadelphia, Pennsylvania, USA.
- Hansbo, S. (1979), "Consolidation of Clay by Band Shaped Prefabricated Drains," *Ground Engineering*, Vol. 12, No. 5, pp. 21-25.
- Holtz, R. D., Jamiolkowski, B., Lancellotta, R. and Pedroni, R. (1991), "Prefabricated Vertical Drains: Design and Performance," Butterworth Heinemann, London.
- Koerner, G. R. (1997), "Field Installation of Prefabricated Vertical Drains," Proceedings of GRI-11 Conference on Installation of Geosynthetics, R. M. Koerner Ed., GII Publication, Philadelphia, Pennsylvania, USA.
- Kremer, R. J., Oostveen, J. P., Van Weele, A. F., DeJager, W. J. and Meyvogel, I. J. (1983), "The Quality of Vertical Drainage," Proceedings of the Eight European Conference on Soil Mechanics and Foundation Engineering, Helsinki, Vol. 2, pp. 721-726.
- Risseuw, P., "Manual for the Attachment of Strain Gauges for Measuring Deformations of Stablenka Reinforcing Fabrics," Enka Industrial Systems, Holland, 1986, p. 23.