Stabilization of creeping slopes by dowels

Stabilisation des pentes en état de fluage par des goujons

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SYNOPSIS Creeping slopes in stiff clay can be stabilized by using dowels made of concrete or steel. The stabilization results in a reduction of the creep rate to a level which is harmless to superstructures. The dowels transmit the stabilizing force from the substratum to the creeping soil. The lateral load on the dowels is assumed to increase linearly up to a maximum value with the displacement relative to the surrounding soil. The design of the stabilization is carried out assuming the dowels as elastic beams with a constant coefficient of lateral subgrade reaction.

INTRODUCTION

In a creeping slope the soil moves slowly downhill. Typical creep velocities are from 0.1 mm per month to 5 cm per month. Usually the ground-water table lies near the surface. The creep velocity decreases and sometimes the creep nearly stops with lowering of the ground-water table. When the water table is raised, creeping begins again. Even small cuts or fills can induce movement of a slope.

Structures on a creeping slope will be influenced by this movement to some extent. A flexible structure, for example an asphalt road, a pipe or a cable, will be unable to resist the movement and will be damaged in due course. In the case of a stiff or inflexible foundation, as e.g. an anchored diaphragm wall or a deeply founded abutment, the soil movement will be slowed down until the build-up of earth pressure due to the creeping soil destroys the structure. Structures of moderate stiffness, as e.g. dwelling-houses, follow the movement while getting increasing cracks.

Usually a creeping slope consists of nearly saturated, stiff clay to a depth of 5 to 15 m - or even deeper. In the transition zone (the thin shear zone) between the moving soil and the stable layer, the water content is usually higher than in the surrounding soil. Often the clay is fissured and therefore the permeability is quite uneven.

In southern Germany creeping slopes are very common. Fig. 1 shows the morphology of a typical creeping slope; the trees are bent and the ground surface is ruckled. From experience people have known about the difficulties in these regions and have avoided to build structures on creeping slopes. Today, however, we often want to construct buildings, roads, and railways in such places. For this to be feasible, geotechnical engineers must provide solutions that are safe, acceptable environmentally, and economic.

Many structures have had to be abandoned because slope movement was ignored. On the other hand it usually requires enormous strength - and therefore high cost - to stabilize a creeping slope totally. In this context stabilization of a creeping slope means reducing the velocity to a level which is harmless to structures. Structures on stabilized slopes must be designed so that the remaining movement will not damage them.

Fig.1 Typical creeping slope

Stabilizing the slope by reducing the angle of the slope can be successful but this is not feasible in most cases. Even a deep drainage does not work in all cases. If a slope is stabilized by drainage and the ground-water table sinks quickly, then the vegetation may be damaged. On the other hand, if the drainage works too slowly, the drains will be damaged by the soil movement; in addition the drains must have a high capacity and they may become sealed by the soil. Electrochemical methods - such as electric osmosis, kataphoresis and grouting - have sometimes been applied succesfully, but their action is not well understood and their design needs some further research and development.

Reinforcement by inserting piles increases the mechanical strength of a slope. If the prevailing loading of the piles is transverse shearing strength, this technique is called dowelling.

Soil dowelling is a rather old invention. In the last 10 years dowels of various diameters and materials have been used. In some cases they have been successful, and in other cases they have not (Sommer 1978, Wichter & Gudehus 1983, Fukuoka 1977).

At the Chair of Soil Mechanics and Foundation Engineering of Karlsruhe University a new design method for dowelling has been devised. The method is briefly outlined in this paper while the formulas, diagrams, and programs can be found in other publications (Schwarz 1984). The method has been tested by means of large scale field tests and by back-calculations. As a result, dowels can now be designed more economically and with greater safety. However, the development of this method is still in progress and further research is needed.

DESIGN METHOD

Considering the creeping slope as a rigid body of weight W which slides on an inclined surface (s. Fig. 2) we obtain the shear force T as

$$T = W\sin\beta \qquad (1)$$

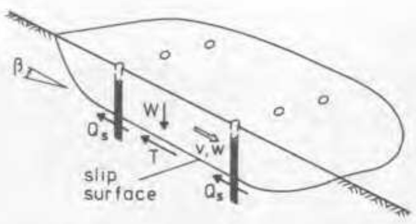


Fig. 2 Creeping slope with dowels

The force T is decreased by the forces Q_s carried by the dowels, and consequently the creep velocity is decreased from v_o to v_1. The latter reduction follows from the assumption that soil is a viscous fluid with a strongly non-linear viscosity which obeys Leinenkugel's (1976) law:

$$T_1 = T_o(1 + I_v \ln (v_1/v_o)) \qquad (2)$$

The viscosity index I_v has values between 0.01 and 0.06 and can be obtained from triaxial tests with variable rates of deformation. Using equ.2 one obtains the number of dowels as

$$n_D = -I_v \ln(v_o/v_1) W\sin\beta/Q_s \qquad (3)$$

When designing the stabilization the values I_v and $W\sin\beta$ are given whereas the ratio v_o/v_1 must be chosen according to the requirements of the structures on the slope. The objective is now to determine the resulting dowel force $n_D Q_s$ for the most economical and safe stabilizing effect. That means:

- the dowels should not be damaged during the design life of the structure. On the other hand they need not be stronger than necessary
- the resisting load from the dowels should be introduced into the soil as early as possible.

The lateral load H depends on the relative displacement u-w as shown in Fig. 3.

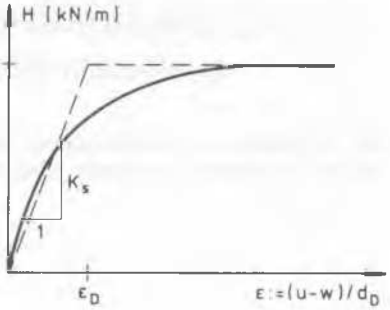


Fig. 3 Load-displacement diagram between dowel and soil

Experiments have shown that the load-displacement curve of Fig. 4 can be approximated by the two dashed straight lines. The maximum lateral load H_f and the coefficient of subgrade reaction K_s are given by the following equations (Gudehus, 1984):

$$H_f \approx 5c_u d_D \qquad (5)$$

$$K_s \approx 5c_u/\varepsilon_D \qquad (6)$$

where c_u is the undrained cohesion, d_D is the pile diameter and ε_D a characteristic strain (usually between 0.02 to 0.10) for the soil being considered. The values of c_u and ε_D can be obtained either from special investigations or from experience of similar situations. Different values occur above and below the slip surface.

To describe the mechanical behavior of a dowel, it is necessary to know the lengths h_o and h_u (above and below the slip surface), the bending stiffness $E_D I_D$ and the ultimate bending moment M_T. The relationship between the displacement w and the horizontal load H is given by the following differential equation:

$$E_D\, I_D\, u^{IV} = H \qquad (7)$$

It is assumed that the displacement inside the creeping part of the slope is constant (i.e. it behaves as a rigid body). Now it is useful to introduce the so-called elastic lengths above (o) and below (u) the shear zone:

$$l_{o,u} = \sqrt[4]{\frac{4\, E_D\, I_D}{(K_s)_{o,u}}} \qquad (8)$$

Depending on whether the ultimate load H_f is reached or not the general solutions of equ. (7) are given by:

$$u = C_{1i} + C_{2i}z + C_{3i}z^2 + C_{4i}z^3 - \frac{H_f}{24E_D I_D} z^4 \qquad (9)$$

and

$$u = \cosh\frac{z}{l}\left(C_{5i}\sin\frac{z}{l} + C_{6i}\cos\frac{z}{l}\right) + \sinh\frac{z}{l}\left(C_{7i}\cos\frac{z}{l} + C_{8i}\sin\frac{z}{l}\right) + \hat{w} \qquad (10)$$

respectively.

The up to 24 constants C_{ij} are determined from the boundary and continuity conditions by solving a system of linear equations. The following equations define $\hat{w}$ and l:

$$\hat{w} = \begin{cases} w & \text{for } 0 \leq z \leq h_o \\ 0 & \text{for } z > h_o \end{cases}$$

$$l = \begin{cases} l_o & \text{for } 0 \leq z \leq h_o \\ l_u & \text{for } z > h_o \end{cases} \qquad (11)$$

The ranges for the equations stated above are determined iteratively.

Three special cases can be distinguished:

Big dowels: For high values of d_D it usually turns out that h_o/l_o and h_u/l_u are both less than 1. The example of Fig. 4 shows that the displacement of the pile is mainly tilting rather than bending. The lateral pressure on the upper and lower parts of the dowel is almost linearly distributed in accordance with the assumption of a linearly elastic subgrade. Usually, the ultimate lateral pressure and the ultimate bending moment are not reached because there is not enough relative displacement w-u during lifetime of the dowel. Therefore the big dowel is not economic. An example of this case (3 m dowels) is given in the paper of Sommer (1978).

The behaviour of small dowels is normally found when $h_o/l_o > 3$, and $h_u/l_u > 3$. As shown in Fig. 4 a small dowel is deflected into an S-shape both in the upper and the lower parts. For distances exceeding l_o and l_u above and below the shear zone respectively, no lateral load is exerted, i.e. there is no relative displacement between pile and soil. An upper part with a length below l_o is loaded by the full ultimate lateral resistance. The transverse force of the dowel (at the level of the shear plane) is obtained from the ultimate bending moment approximately as:

$$Q \leq M_T/(1.3\, c_u\, d_D) \qquad (12)$$

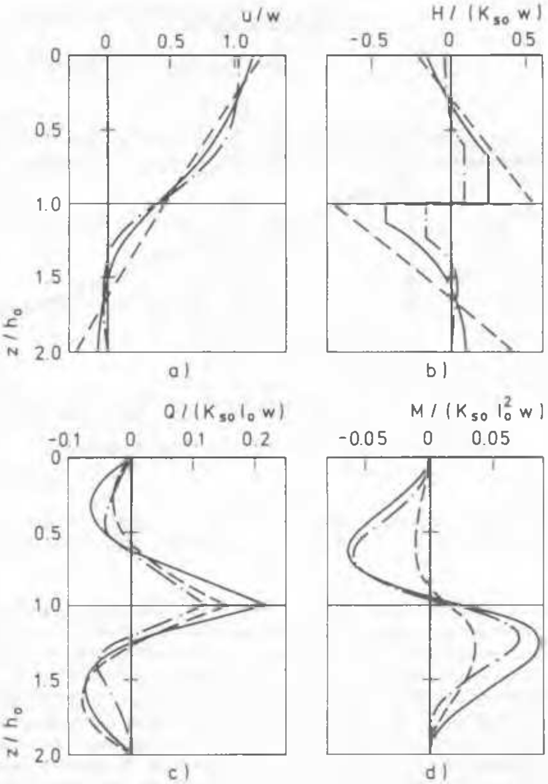
Although their strength is fully utilized, small dowels are often uneconomic, since only a small section of them is stressed. Moreover, a large number of dowels is needed and this leads to high installation costs.

The optimum dowel has h_o/l_o and h_u/l_u values between 1 and 3. This ensures the optimum utilization of the pile strength and the soil strength (s. Fig. 4).

The optimization has been carried out by a computer program given by Schwarz (1984). However, for a preliminary design the diagrams given by Gudehus (1984) may be used as well. The optimum diameter is roughly 5 % of the depth to the slip surface.

When using this design method the design should ensure that the chosen dowels are as easy to install as possible and are distributed in such a way that the soil cannot flow between them. It should be noted that the dowel action only occurs after a lapse of a time which is needed for the displacement to mobilize a sufficiently high lateral force. Analytical expressions and extrapolation methods to predict this behavior have been given by Schwarz (1984).

The success of the design is very sensitive to the values chosen for the parameters needed in the analysis. These values should be reduced by appropriate factors of safety. In difficult situations the success of the stabilization should be checked by control measurements (such as geodetic and inclinometer measurements).



signature	h_o/l_o	h_u/l_u	l_o/l_u
– – – – – big dowel	0.9	1.1	1.2
—·—·— small dowel	3.8	4.2	1.2
——— optimum dowel	2.4	2.7	1.2

Fig. 4 Calculated curves for dowels
a) deflection b) lateral load
c) transverse force d) bending moment

CASE STUDIES

a) Landslide at Dautenheim
A 8 m high fill embankment for the motorway A 61 was errected on a slope with an angle of 5°. After some years significant creeping began. The position of the sliding surface was identified by means of inclinometer measurements (s. Fig. 5) and was found to be located in a stiff tertiary clay ($c_u \approx 150$ kN/m^2, $I_v \approx 0.03$).

The landslide was stabilized by two rows of 1.5 m diameter dowels. The distribution of the dowels is shown in Fig. 5. The former creep rate of 0.1 to 0.15 cm/day was reduced to a rate which was not measureable over the period of a few months. Possibly the lowering of the ground water table also contributed to this result.

b) Large scale field test Geislingen(I)
A slope with an angle of 18° to 20° in a stiff, fissured jurassic clay (c_u = 150 kN/m^2, I_v = 0.035) was cut for a railway track 100 years ago.

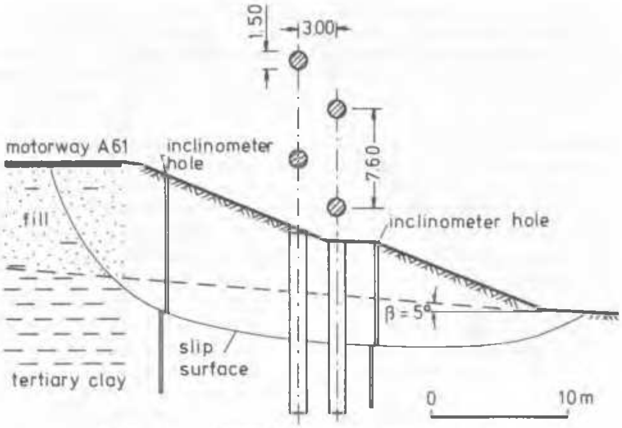


Fig. 5 Dowelling at Dautenheim

There have been creep movements since then. On this site a field test for dowelling was carried out.

Fig. 6 shows the cross section of the slope, the mechanism of failure (detected by inclinometer measurements) and the two rows of dowels. The latter were made of reinforced concrete with a diameter of 0.4 m. Within a control interval of 25 weeks the creeping velocity was reduced from 4.7 mm/month to about 1.3 mm/month. Since then, for financial reasons, no further measurements have been carried out. A detailed description of this project has been given by Schwarz (1984).

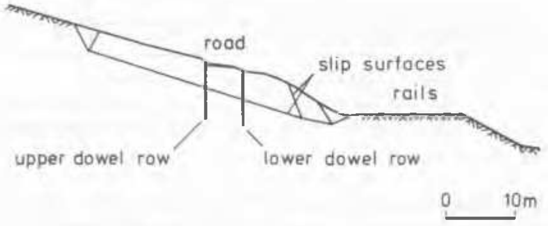


Fig. 6 Cross section of the test field Geislingen I

c) Large scale field test Geislingen(II)

A part of the slope described above was stabilized with "grouted" dowels. Steel tubes of 1.5' and 2' diameter were introduced into pre-bored holes. The latter were sealed with a suspension of cement and silica. Four different dowel distribution densities were tested (s. Fig. 7).

The success of the stabilization depended on the dowel distribution density. The test with the lowest dowel-density was not stabilized at all. In the other tests a reduction of the creep velocity was achieved. As expected with the small diameter dowels, the stabilization set on quickly, but later the dowels were destroyed due to the progressively increasing load. For more details s. Wichter & Gudehus (1984).

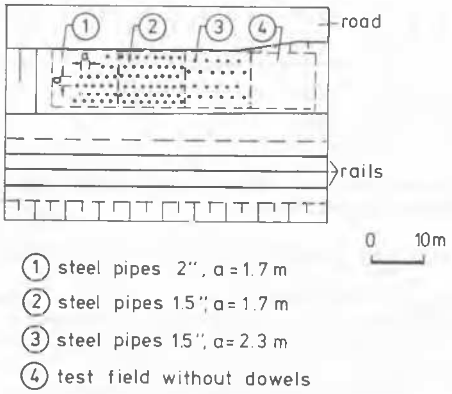


Fig. 7 Situation of the test field Geislingen (II)

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