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Experimental studies for the increase of slope stability of historical embankments due to the effects of capillarity and vegetation

Études expérimentales sur l'augmentation de la stabilité de pente d'anciens remblais due aux effets de la capillarité et de la végétation

R. Katzenbach & A. Werner
Institute and Laboratory of Geotechnics, Technische Universität Darmstadt, Germany

ABSTRACT
The performed stability analysis of historical embankments demonstrate that the application of conventional and standardized calculation methods theoretically yields instability of the embankments due to their geometry, soil properties and without consideration of stabilizing effects. By applying the enhanced concept of Experimental Statics consisting of large field and laboratory tests, it is possible to verify the real stability of the embankment.

RÉSUMÉ
Des calculs à rebours de stabilité d'anciens remblais montrent que l'application de méthodes de calcul conventionnelles et normalisées mène à l'instabilité théorique de ces remblais due à leur géométrie, les propriétés du sol et la non-prise en compte d'effets de stabilisation. En appliquant le concept amélioré de la « Statique Expérimentale » consistant en essais en vraie grandeur et tests en laboratoire, il est possible de vérifier la stabilité réelle du remblai.

1 INTRODUCTION

Conventional slope stability analyses (Bishop 1955; Taylor 1948) are usually based on the effective strength parameters for the natural sediment (e.g. sand), grain size distribution, relative density and the geometry of the embankment. For many sand slopes, to a great extend are unsaturated, this is not sufficient to explain the existence of steep geometrical configurations ($\beta > \varphi'$) (Raju & Khemka 1971). The calculated factors of safety often become very low, in extreme cases resulting in evacuation of the area affected and in closing of roads. This has emphasized the need for increases knowledge of the properties of the unsaturated zone in general and the influence of matric suction in particular. Better knowledge makes it possible to estimate the consequences of different external factors affecting the stability, such as precipitation, vegetation etc.

In the following results of stability analysis carried out on historic railway embankments of sandy fill with steep slopes are presented. The performed stability analysis demonstrates that the application of conventional calculation methods theoretically yields instability of the embankments. The computed factors of safety range between 0.9 and 1.1.

By the use of the concept of Experimental Statics it is however possible, to verify the true stability of the embankment. Furthermore this paper presents some measurements of matric suction at this test side A.

The influence of roots on the shear strength characteristics of non-saturated soils is presented in this paper using the new shear apparatus at test side B.

2 GEOMETRY AND SOIL PROPERTIES OF THE HISTORICAL EMBANKMENT

The investigated earth embankments were built without compaction in layers of the fill towards the end of 19^{th} century, which is a typical situation for historic railway embankments.

The embankments are 4 m to 10 m high with slope angles β up to 40°. The investigated earth embankments are abundantly covered at the slopes as well as the crests with vegetation, e.g. by trees and shrubs of various types.

At test side A (Fig. 7) the embankment fill and the subsoil were investigated by a drilled boring of 10 m depth and a dynamic probing test. The soil samples revealed a 5.2 m thick stratum of fine to middle sand with small amounts of silt. It is very loosely up to loosely packed. This fill material is underlain by the natural soil consisting of gravely middle sand with small amounts of fine sands which is medium-dense packed. The embankment fill has the following average characteristics: unit weight of 17.0 kN/m³, angle of friction of 30° and cohesion of 0 kN/m². The modulus of deformation is determined for the initial loading to 4 - 9 MN/m² and for the reloading between 14 - 19 MN/m² carried out by plate load bearing tests according to DIN 18 134 in a depth of 1.5 m below dam crest. The groundwater level is located at the bottom of the slope of the embankment.

2.1 *Stability analysis*

For the stability analysis using Bishop's method, different failure mechanisms are investigated (Katzenbach and Fehsenfeld 2002). The performed stability analysis demonstrates that the application of this conventional and standardized calculation method theoretically yields instability of the historical embankments due to their geometry and soil properties. The computed factors of safety for the slopes range between 0.9 and 1.1. This result contradicts the experience. Because there are mechanisms in the soil increasing the factor of safety, but they must not take into account for"classical" calculation methods evaluating the stability of slopes.

2.2 *1:1 loading test with the loading vehicle BELFA*

The Experimental Statics Method (ESM) is based on the idea of proofing the stability of an earth embankment by special field investigations, e. g. loading-tests on the scale of 1:1. The above described, theoretically instable embankment was tested by the experimental Statics Method. A load was applied on the embankment by the loading-vehicle, called BELFA (Fig. 1).

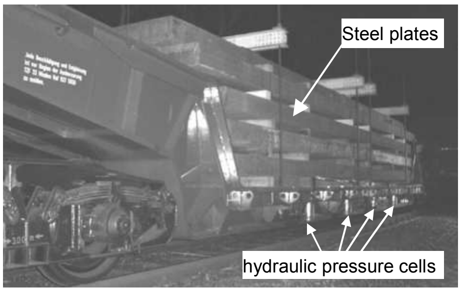

Figure 1. Loading-vehicle BELFA

BELFA is a 31 m long vehicle weighing 90 t equipped with additional ballast of 160 t consists of steel plates. The test load was applied by 2 x 4 hydraulic pressure cells placed on the tracks under the loading vehicle. The force on the hydraulic pressure cells reached 225 kN each, so that the overall technical test limit load was increased continuously up to 1,800 kN that is an equivalent pressure load of 125 kN/m². This equals twice the design value of the traffic load according to the German guideline RIL.

Measurements of deformations of the earth embankment during the loading test were carried out by displacement transducers installed at the bottom of the ballast. Additional extensometers and inclinometers were installed in the fill.

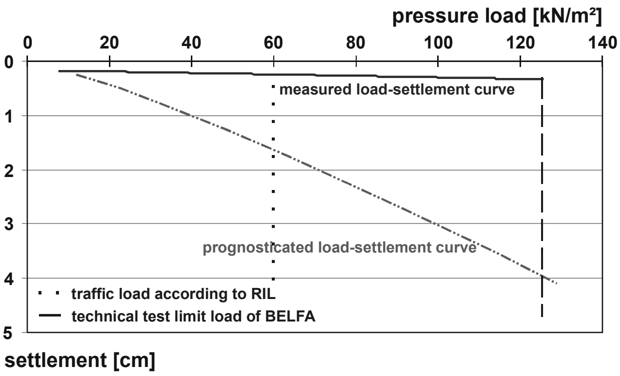

Figure 2. Load-settlement curves: Prediction versus Finite-Element Prediction

The displacement transducers measured maximum settlements of 0.4 cm during the maximum loading-step. Figure 2 compares the prognosticated with the observed load-settlement curve. The prediction based on a finite-element analysis applying modulus of deformation of E = 20 MN/m² and computed settlements 10 times the magnitude of the measured values.

The extensometer revealed maximum settlements of 0.4 mm, which is very small, at a depth between 1.5 m and 3.5 m below the crest during the maximum load step of 1,800 kN. Horizontal displacements of 0.8 mm towards the slope face were measured by the inclinometer. This value lies in the range of accuracy of the measurement.

The 1:1 loading-test on the theoretically instable embankments using the loading vehicle BELFA shows that there are additional mechanisms increasing the stiffness and the load bearing capacity of the existing embankments. These mechanisms include:

- Vegetation, i.e. roots
- Soil moisture (Capillary effects)

3 VEGETATION

It is well understood that vegetation influences slope stability in following ways: (1) By mechanical reinforcement from the plant roots; (2) by increasing in soil suction or reduction of pore water pressure, hence, an increase in the soil shear strength, through the removal of soil water by evaporation through vegetation; (3) by surcharge from the weight of trees; and (4) by "wind throwing" or root wedging". The first three increase the strength or stability of a soil; the fourth tends to decrease stability, because it transmits wind dynamic forces to roots which may cause loosening of soil influenced by the root networks or increasing the destabilizing force. Of the first three aspects, the mechanical reinforcement by roots and the soil moisture are probably the most important and are treated further in the following section. The surcharge due to the weight of the vegetation may not be beneficial to the stability of slope. Figure 3 shows the main influences of vegetation after Coppin and Richards (1990) on a stability of a slope segment.

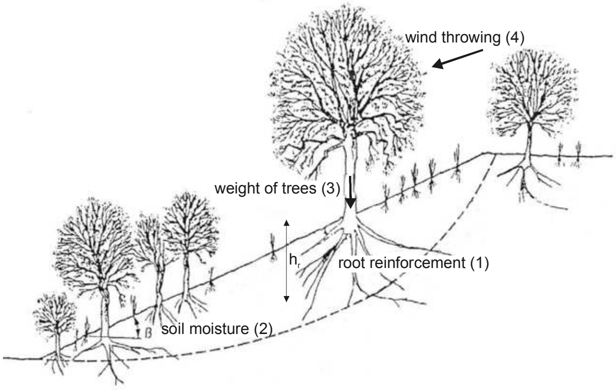

Figure 3. Main influences of vegetation on slope stability

The calculations of the factor of safety presented in Morgenstern and Rickson (1995) demonstrate that the vegetation increases the factor of safety by 55 %, assuming that the tensile strength of the roots is fully mobilized. In a case study Greenway (1987) found that the additional cohesion brought about tree roots increased the factor of safety on wooded slopes in Hong Kong by 29 %.

Before delving into our field experiments to find out the increase of shear strength through mechanical reinforcement by roots of shrubs at test side B, it is essential to point out how difficult it is to determine the depth of the root zone h_r for slope stability analysis. For example the roots of shrubs extend to 0.5-1.0 m below slope surface and herby they play an important role in stabilizing shallow-seated failure of slopes. Tree roots can spread out for considerable distances. The extent of root spread is normally reported in relative multiples of the tree height or crown radius (Morgenstern and Rickson 1995). A useful rule of thumb is that a root system will spread out a distance at least equal to the 1.5 times the radius of the crown (mechanical reinforcement). The hydraulic influence of a tree, that is, significant soil moisture, reductions by evaporation, can be felt to a distance of at least one times the tree height for a popular tree (Populus deltoids) growing in Boulder clay (Morgenstern and Rickson 1995).

Some interesting research has been carried out by Wu et al. 1979, Waldron and Dakessian 1981). Most of them show that roots increase the apparent cohesion (c_r) component of the shear strength. Tobias and Grubinger (1988) identified on grass-soil systems that root permeated soil has an influence on both parameters and therefore the shear strength can only be mentioned as an integral value.

First field studies were carried out using our large new designed shear box apparatus to identify soil-root parameters of shrubs. Figure 4 shows the schematic drawing of the apparatus.

The size of the box measured 50 cm × 50 cm with the height of 25 cm. The normal load σ was applied by means of steel-plates and the horizontal and the vertical displacement was measured by using displacement transducer. The horizontal shear force, applied by a hydraulic press, affecting in the shearing surface according to DIN 18137-2.

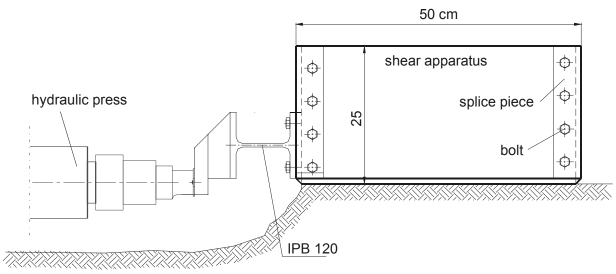

Figure 4. Schematic drawing of designed large shear apparatus

The specimens are sheared at 0.1 m to 0.2 m depth at a constant shear displacement rate of v = 0.8 mm/min. The normal stresses applied were small, ranging from 7 kN/m² to 30 kN/m². The natural water content during testing was about 10 % of the loosely packed sandy soil. After each field test, the roots were collected and the diameter of the roots was measured.

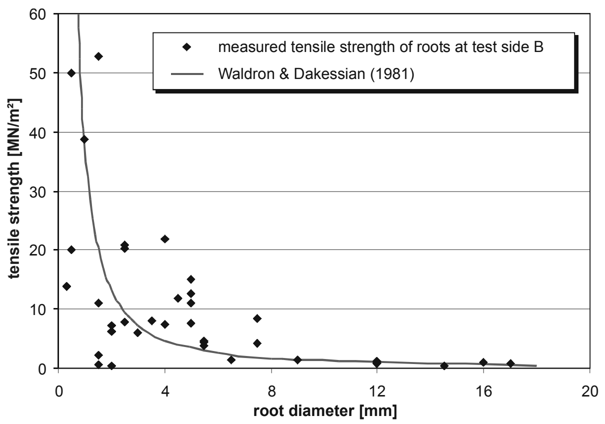

Figure 5. Tensile strength of roots in relation to the diameter

In field tensile tests the tensile strength was measured where the roots were tensioned out of the sandy soil. Smaller diameter roots have larger tensile strength than bigger ones. Figure 5 illustrates this point. This may be explained by the fact that smaller roots of shrubs are more fibrous and further more in bigger roots the skin tends to tear off during tensile test. Nearly all roots are broken off above ground surface. In figure 5 the continuous line based on an exponential relationship after Waldron & Dakessian (1981).

Shear tests in the laboratory of rootless soils were carried out, too. The tests were run under the same conditions compared to the field tests. The angle of friction φ under laboratory conditions was between 28° - 30° and the apparent cohesion was found between 3.2 kN/m² and 4.5 kN/m² for water contents ranging between 0 % and 15 %. It is well known when the water content changes, the apparent cohesion also varies.

Figure 6 shows the relationship between the shear strength τ plotted on the y-axis and the applied normal stress σ plotted on the horizontals axis for the field and laboratory shear tests. The shear strength τ from the field tests is outlined against the intensity of roots N_{WG} (= number of roots in the total shear cross sectional area) (Hähne 1991). The increase in the shear strength for root reinforced soils is identifiable; the shear strength of all field tests is above the shear strength of rootless soils.

One theoretical root reinforcement model described by Gray & Leiser (1982) was used to predict the increase in shear strength. The shear strength increase, ΔS, according to this model is:

$$\Delta S = 1{,}15 \cdot T_R \cdot \frac{A_R}{A} \quad (1)$$

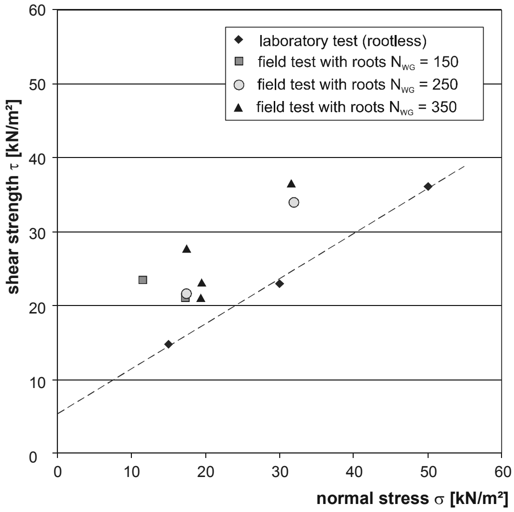

Figure 6. Shear strength subject to the intensity of roots N_{WG}

where T_R is the average tensile strength of the roots, A_R is the total roots cross-sectional area and A the total shear cross-sectional area. The total shear strength τ of the soil-root-system can be found by adding the shear strength increase, ΔS, to the usual expression for shear strength after Coloumb:

$$\tau = c' + \Delta S + \sigma_N \tan\varphi' \quad (2)$$

The analysis of the total shear strength using formula 2 results in discrepancies to the actually measured shear strength. For field shear tests with a natural water content of about 10 % there is a great discrepancy between the measured and calculated shear strength. Minor differences are calculated for the field tests with water contents about 20 %. It might be the cause of that Waldron & Dakessian (1981) developed the equations for soils under saturated conditions and for cohesive soils.

4 SOIL MOISTURE

The first mention of soil suction in slope stability studies was made by Terzaghi (1950). Since then, many field works have been undertaken to study the effect of matric suction on slope stability (Öberg 1995). When the maxtric suction values have to be taken into account in stability analysis the results become more concordant with the existing steep configurations and observed sliding activities, than the results obtained by conventional stability analysis.

4.1 *Mactric suction measurements at test side A*

The mactric suction profile in the historical embankment is studied by using tensiometers installed in the unsaturated fill. They consist of a porous, high air-entry ceramic cup which is filled with airtight water. While the soil is dry, the water moves out of the ceramic cup in response the natural capillary forces within the soil. The reverse process takes place when the soil is wetted. When the soil is saturated with water, the matric suction is zero. The negative water pressure that can be measured with a Tensiometer is limited to approximately 80 kPa.

Altogether 21 tensiometer are installed in the embankment at different depths to study the matric suction profile ranging from the dam crest to the dam base both in the center of the dam and along the slope in order that the influence of vegetation, i.e. the depth of the root zone h_r and the influence of water (evaporation, precipitation) can be identified. At each depth three tensiometer are installed. Furthermore 7 TDR (Time Domain Reflectometry)-probes are located at the same depths.

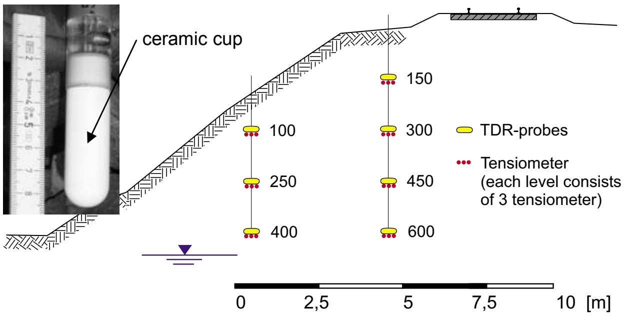

Figure 7. Section of test side A with installed Tensiometer and TDR-probes

Throughout the regular monitoring of the 21 tensiometer stations enabled a regime of soil suction against time to be established for the tensiometer 100, 250 and 450 in Figure 9. The period of measurement in February 2003 to October 2004 the matric suction fluctuates considerably during the winter and summer month at shallow depths abundantly covered with vegetation (Tensiometer 100 and 250). In particular, in May to September, in dry periods, the depth of the root zone is definable. Tensiometer 250 located in 2.50 m below slope surface are influenced by roots whereas Tensiometer 400 installed at the same depth, 4.0 m below crest surface send suction values which are rather constant during the period of observation. In the same period after a heavy rainfall the plants extracts water from the soil to compensate for water lost to the atmosphere via transpiration. This process lowers pore-water pressure in the soil and therefore improves slope stability, as well. At magnitudes greater ~80 kPa they are failed and the measured soil suction is reduced to zero. In the winter months average suction values vary in a range not exceeding 10 kPa.

5 SUMMARY AND CONCLUSIONS

The results of the 1:1 loading-test with BELFA at the historical embankment indicate that the choosen geotechnical concept is a technique to prove practically the slope stability.

In further research the embankment is investigated in a back analysis by using the results of 1:1 loading-test and the “modified” shear parameters, such as considering the influence of the interaction of vegetation and soil moisture obtained by geotechnical measurements. As state of the art analysis in a next step the modified shear parameters have to introduce in the conventional analytical calculation methods.

Because the modified shear parameters are functions of soil moisture and rainfall, temperature, amount and type of vegetation the consequent application of the observational method is necessary.

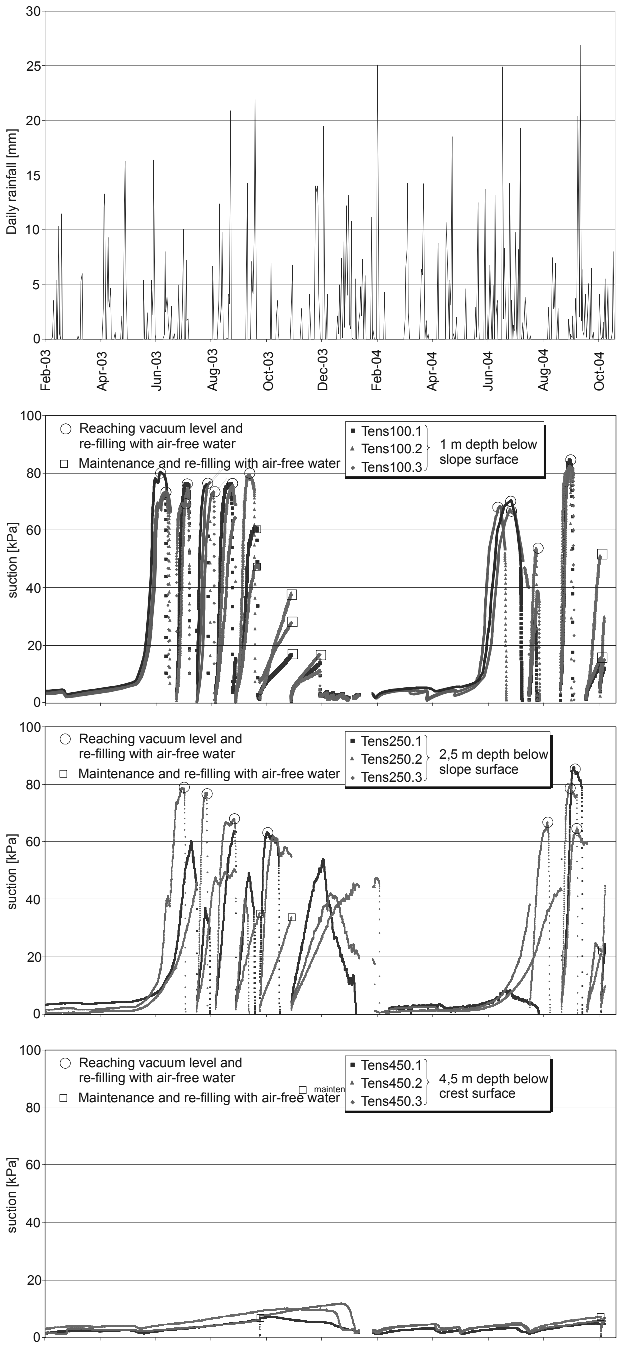

Figure 8. Matric suction contours along a section of the embankment

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