Investigation of Road Widening on Soft Soils Using a Small Centrifuge

H. G. B. ALLERSMA, L. RAVENSWAAY, AND E. VOS

Increasing traffic in the Netherlands increases the demand for roads to be widened. In several cases the sand body of the roads is founded on soft soils. To widen these roads, the width of the sand body has to be increased. The widening process can cause cracks in the asphalt layer of the original road, which has to be prevented as much as possible. To investigate the effect of different methods of road widening, a test program was carried out in the small geotechnical centrifuge of the University of Delft. Two different methods of widening were simulated: the horizontal method and the gap method. The excess pore water pressure was taken into account, and the deformation of the clay layer and sand body was measured by means of image processing. Although the differences in deformations measured were small, it could be seen clearly that the horizontal widening method caused more horizontal displacements than the gap method. This indicates that cracking of the asphalt layer could be minimized by using the gap method of construction.

In the western Netherlands the subsoil consists of a thick layer of soft soils, such as peat and clay. In some cases traditional road widening on these soft soils causes serious problems, such as large settlements. For example, the motorway from Rotterdam to Antwerp was widened during 1988–1990. In the sections close to the Van Brienenoord Bridge, embankments higher than 5 m were needed. The subsoil at that location consists of peat and soft clay layers with a thickness of more than 10 m. The subsoil was already covered with a thick layer of sand to obtain an embankment as a base for the asphalt pavement. It was decided to construct the widening of the embankment in stages of horizontal sand layers of 0.5 m a month. During construction it was found that serious longitudinal cracking occurred in the existing asphalt pavement. To eliminate or reduce this cracking, it was decided to modify the construction method, first constructing an embankment close to the existing embankment and then filling the remaining gap. It was expected that this so-called gap method would lead to a reduction in horizontal deformations in the existing embankment and consequently a reduction in the cracking of the asphalt pavement. The gap method was applied in the last sections of this widening project. The consensus is that a reduction in the cracking can indeed be achieved.

Because more roads in the Netherlands have to be widened, the Road and Hydraulic Engineering Division of Rijkswaterstaat initiated a research project to study this subject in a more consistent and systematic way. It was decided to study this problem both numerically (*1*) and experimentally. The experimental approach, discussed in this paper, focuses on a comparison of the two construction methods in well-defined experimental conditions using scale models in a centrifuge. Very little centrifuge research has been done on the widening of embankments. Most of the embankments investigated in a centrifuge were embankments stabilized by reinforcement (*2*) or founded on consolidated clay (*3*)

A test program was carried out in the small geotechnical centrifuge of the University of Delft to investigate the effect of different methods of widening embankments founded on soft soil. Most tests were performed on a clay layer with a thickness of approximately 0.07 m. At 100 *g* the same shear stresses can be simulated as in a clay layer of 7 m, so a small model in the centrifuge behaves in a manner similar to the prototype. The soft clay sample was prepared by consolidating a clay slurry in a centrifuge. The widening of the original sand body was performed in flight by means of a sand pluviation machine. The position of the hopper and the amount of sand to be sprinkled during translation of the hopper was controlled from the keyboard of a personal computer (PC). Different widening methods were simulated and the excess pore water pressure was taken into account. In centrifuge tests the same pore water pressure can be generated as in reality. Because the real dimensions of the model are a hundred times smaller than the prototype problem, the consolidation time is reduced by the square of the artificial gravity. The deformation of the clay layer and sand body was measured by means of image processing on the PC. A special technique was developed to copy a grid on the surface of a black or white clay without removing boundaries, and the reproducibility of the samples was extremely good, which was essential for visualizing the slight differences caused by the different widening procedures. As far as possible the test results were compared with numerical calculation methods.

The soil parameters were determined in the laboratory by compression tests and triaxial tests, and in-flight vane tests were used to investigate whether the clay was homogeneous and whether all clay samples had the same strength. Embankment tests were performed to validate the soil parameters found and investigate whether the clay model behaved as expected. From these embankment tests the maximum embankment height was found. To investigate the two widening methods, several tests were performed. The pore pressure measurements were used to determine the waiting time between the construction of the different layers.

EQUIPMENT

Investigations of the different methods of embankment widening were conducted using the small geotechnical centrifuge at the University of Delft (*4*). One disadvantage of a small centrifuge is the limitation in the use of sensors during a test. This restriction, however, is partly compensated for by applying image processing techniques to the video images obtained from the onboard video camera (*5,6*). Image processing software digitizes the coordinates of the nodes of a grid on a clay surface. Because the grid can be copied on

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the clay surface without removing the transparent boundaries, the deformation of soft clay layers can be monitored accurately.

Sand Sprinkler

A computer-controlled sand sprinkler was developed to make embankments in flight (Figure 1). The sand hopper and sprinkler system can be translated over a range of 150 mm. Several options can be assessed in the control program, and it is possible to sprinkle sand layer by layer or at one particular location. The disturbing effect of the Coriolis forces is minimized by means of hinged sheets that guide the sand grains. The sand sprinkler's control program also reads the output of pore water pressure transducers, which can be placed in the clay layer. The pore water pressure changes in the clay layer are plotted on the PC screen while the embankment is under construction. The emergence of a dike during sand suppletion can be monitored by a video camera.

In-Flight Vane Apparatus

To correlate test results with calculation methods, information is needed about the properties of the soil types used. In the case of clay, the way in which the undrained shear strength changes with the depth during the test must be known. Information about the shear strength can be obtained by means of an in-flight vane apparatus. The undrained shear strength is calculated from the torque and the surface of the cylindrical soil unit, which is rotated by the vane. In this particular investigation the rotation speed of the vane was approximately the same as the speed in the slip circle in the clay during failure of a dike in the centrifuge. The position of the vane can be adjusted over a range of 250 mm during flight so that several tests can be performed without stopping the centrifuge.

CLAY PREPARATION

Clay slurry with a water content of approximately 100 percent is homogenized in a mixer before it is put into sample boxes. A new technique has been developed to obtain an air-free mixture of clay powder and water under normal atmospheric conditions. The best way to obtain a soft, normally consolidated soil with a smooth and realistic gradient of water content and strength over the height of the sample is to consolidate the slurry in the centrifuge at the same *g*-level as will be used in the tests. The sedimentation and consolidation of Kaolin clay takes approximately 8 hr. Because the centrifuge will be occupied during that time, no other tests can be performed. Therefore a special centrifuge was built exclusively to consolidate the clay layers.

RESULTS

Embankments

Embankment tests were performed to determine the maximum height of an embankment founded on a layer of Kaolin clay. The embankment was made in flight, at 100 *g*, by means of the computer-controlled sprinkler device. After the sample was fully consolidated in the centrifuge, the sand was dropped at one place, and the slope of the embankment appeared to be 30 degrees. The sand was dropped until the clay collapsed. Because this procedure took less than 1 min, the test was considered to be performed under undrained conditions. The slip circles could be seen clearly by the grid made on the clay.

In Figure 2 the slip circle can be seen going almost through the center of the embankment. This is in agreement with the Bishop theory. The maximum height was 0.043 m, which translates to 4.3 m in reality.

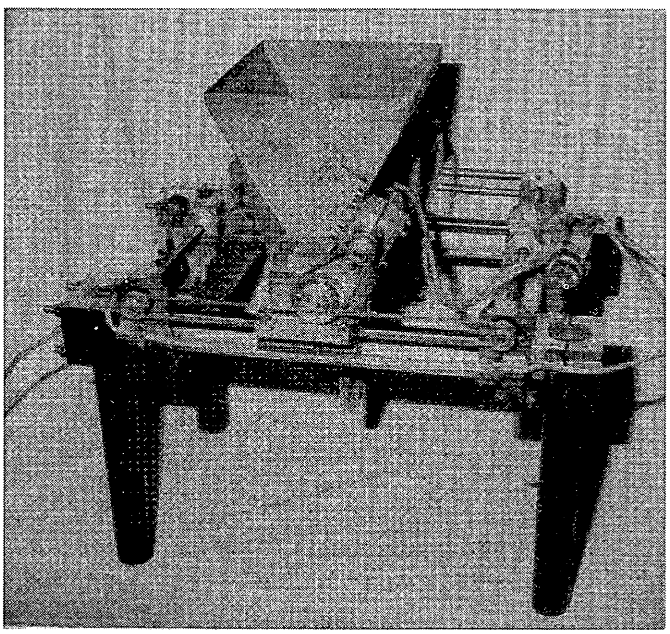
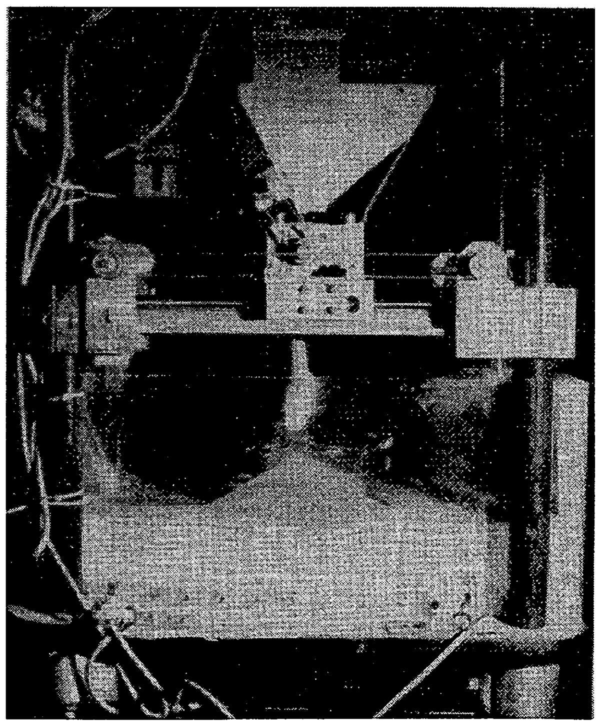


FIGURE 1 In-flight sand sprinkler.



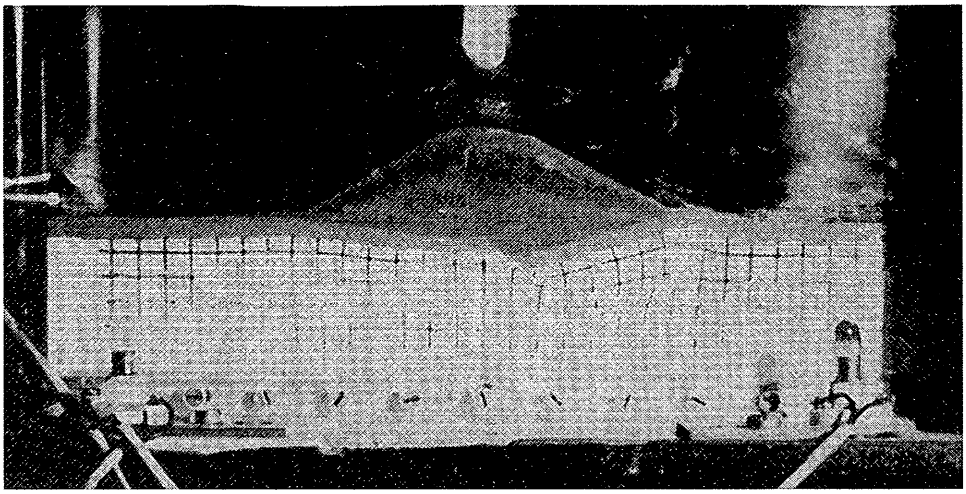


FIGURE 2 Collapsing embankment.

The safety factor of this embankment was calculated with two computer programs, Stabil and PLAXIS. Table 1 presents the soil parameters used for the calculations. These soil parameters were determined by compression tests and triaxial tests. The undrained shear strength at some depth was determined with the in-flight vane test.

Stabil calculates the safety factor of a slip circle according to the modified Bishop method. The soil parameters needed are the specific weight and the cohesion for every layer. Figure 3 shows the most critical slip circle as calculated by Stabil. The safety factor was 0.771.

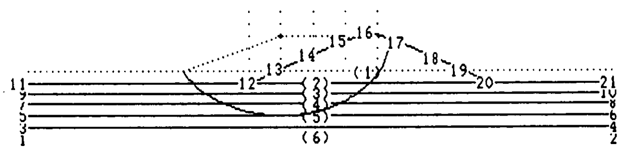


FIGURE 3 Critical slip circle, derived with Bishop method.

PLAXIS (*7*) is a finite element program for soil construction calculations. All parameters presented in Table 1 are needed in this program. The incremental displacements of the final step calculated by this program are shown in Figure 4. The safety factor calculated with this program was 0.859.

Both calculation methods gave lower safety factors than did the test results. This could be because of simplifications in the computer simulations; for example, in Stabil the cohesion cannot be varied with the depth, and in PLAXIS the cohesion cannot be taken as equal to zero. A time effect could be another reason for the deviation. After the embankment has reached the critical height, it appears to take several seconds before the soil collapse. In this time interval the hopper still continues to drop sand, so the embankment becomes oversized. The development of a slip circle takes some time because water has to flow to the slip circle surface to permit dilatation. Because of this time effect it is difficult to find the exact moment of failure.

TABLE 1 Soil Parameters Used in Analytical and Numerical Calculations

SAND			
unit weight	γ_{wet}	20.5	kN/m^3
friction angle	ϕ	31°	
cohesion	c	0	kPa
CLAY			
unit weight	γ_{wet}	17	kN/m^3
Poisson ratio	ν	0.35	
Ko		0.57	
cohesion versus depth	Cu/σ'_v	0.40	
elastic shear versus depth	G/σ'_v	4.81	
permeability	k	2.5*10^{-9}	m/s

From these embankment tests it can be concluded that the centrifuge is a good testing tool; the soil collapsed according to a slip circle, as expected. The calculated safety factor based on the dimensions of this test was close to 1, which is also an indication of the reliability of the test method.

Embankment Widening

Widening tests are performed at 100 *g* on a clay layer with a thickness of 0.07 m and embankment heights of approximately 0.04 m. This conforms with a prototype condition of 7-m clay and an embankment with a height of 4 m. Two different methods to widen embankments were investigated and compared: the horizontal method and the gap method. In the horizontal method the widening is made of horizontal layers. In the gap method, first a new embankment is constructed at some distance from the existing embankment, and then the gap is filled. These tests were performed to investigate the existence of differences in the deformations of the existing embankments and to determine whether the differences could be made visible. Such deformations, especially horizontal displacements, can be the cause of horizontal cracks in asphalt roads.

The existing embankment was made at 1 *g* and was 0.04 m high. This height was measured to be sure that the existing embankment did not collapse, as happened at 0.043 m at 100 *g*. Beads were placed in the embankment, and on the clay layer a grid was connected to follow the deformations. Two pore-pressure transducers were

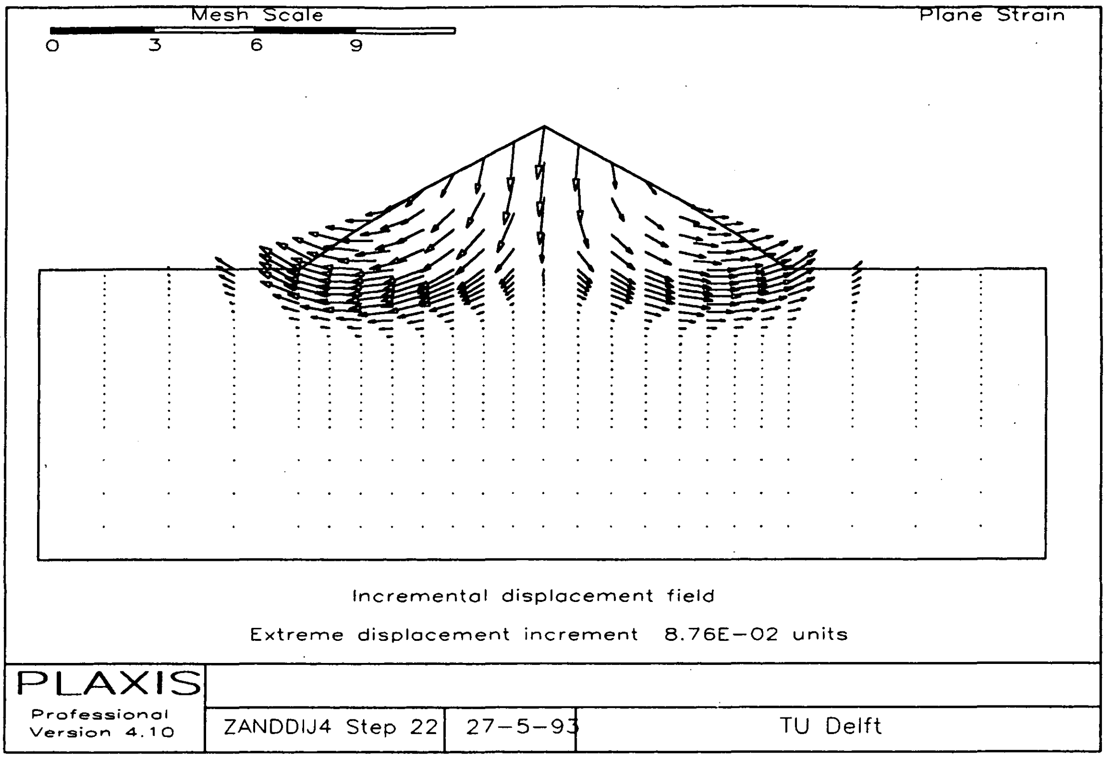


FIGURE 4 Result of numerical calculation.

placed in the clay layer, one located where the top of the widening would occur and one located under the existing embankment. To prevent the excess pore pressures from becoming too high, the acceleration was brought up to 100 *g* in steps of 1 *g* every minute.

After the clay layer was fully consolidated, the widening process was started. The widenings were made in flight with the help of the sand sprinkler. The test was observed from the control room by means of a camera. The widening part had a maximum height of 0.05 m, depending on the drainage during the test.

Three tests were conducted to investigate the stability of an existing embankment when a new embankment is constructed nearby. In the first test the new embankment was constructed at some distance from the existing embankment. In the second test the new embankment was constructed at the toe of the existing embankment, and in the third test the top of the new embankment was located at the slope of the existing embankment. All the embankments were constructed as quickly as possible, in approximately 30 sec (roughly 83 hr in prototype conditions).

Figure 5 shows the results of the first test. The top of the new embankment was made at 0.02 m from the toe of the existing embankment. As can be seen, the soil collapses according to a slip circle. It can also be seen that only the new embankment collapsed, and that nothing happened to the existing embankment. The displacements of the beads in the existing embankment were followed during the test, and they also showed no significant deformations. The most peculiar phenomenon is that not even a small part of the existing embankment collapsed. The other two tests, as described previously, were performed slightly closer to the existing embankment. The new embankments did not collapse and the influence on the existing embankment was not significant.

From these tests the conclusion can be drawn that the location of the new embankment is important. If there is a large overlap between the two embankments, the soil is too strong to collapse. If the embankment is constructed at some distance from the toe of the existing embankment, the new embankment collapses and the existing embankment is not affected dramatically.

Several tests were performed to compare the two widening methods. The pore pressure readings were used to determine the waiting time between the application of the different layers. The waiting time was 1,500 to 2,000 sec in the test, which is 173 to 230 days in reality.

The horizontal method (Figure 6) involved four layers of approximately 0.0125 m each. The first layer was constructed after the clay was fully consolidated. While sprinkling sand, the hopper moved two times between the outermost point of the widening and the toe of the existing embankment. After the layer was constructed, the pore pressures were measured and the readings used to determine when to construct the next layer. The process was repeated for the third and fourth layers. Figure 6 also shows the location of the two pore pressure transducers (PPTs).

Using the gap method (Figure 7) a new embankment was built at some distance from the top of the existing embankment. This embankment again consisted of four layers of 0.0125 m each. After the fourth layer was constructed, the gap was filled in one action.

The pore pressures were measured for all the tests. Figure 8 shows the excess pore pressures for the two widening tests. After the suppletion of the first layer, the next layer was supplied only after a reduction of the excess pore pressures to almost zero. This process was repeated for the next layers. The fifth peak that can be seen in Figure 8 (bottom) was the filling of the gap. PPT 1 was

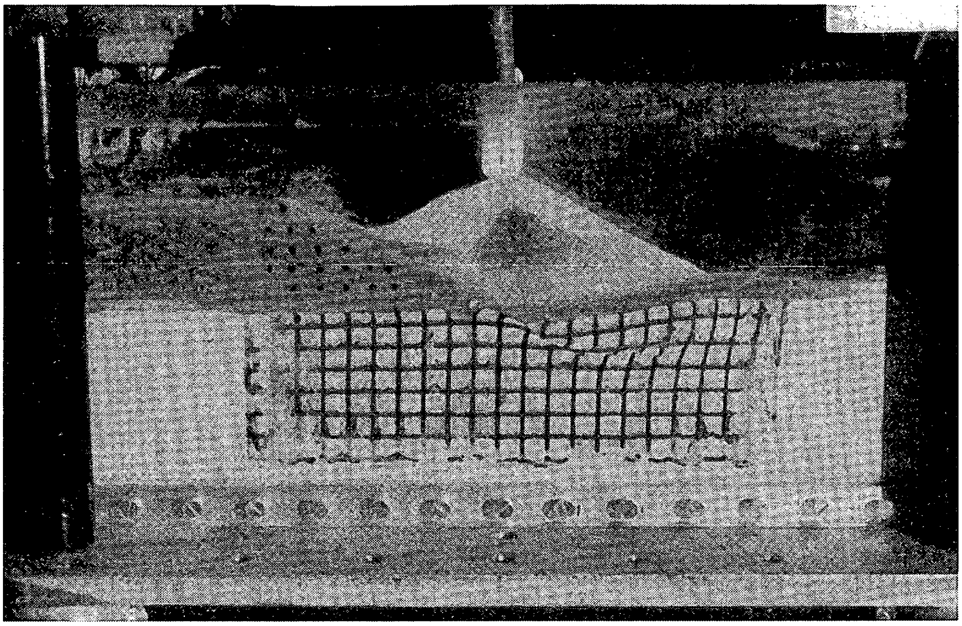


FIGURE 5 Collapse of new embankment.

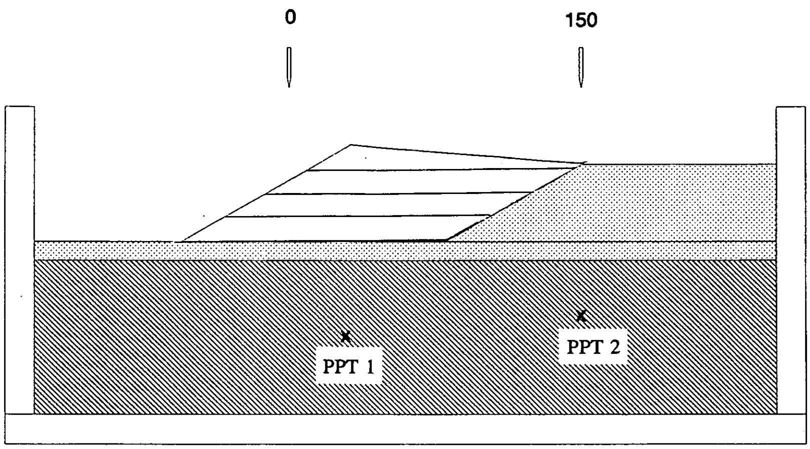


FIGURE 6 Horizontal widening method (dimensions of sample box: l = 410 mm, h = 165 mm, b = 150 mm).

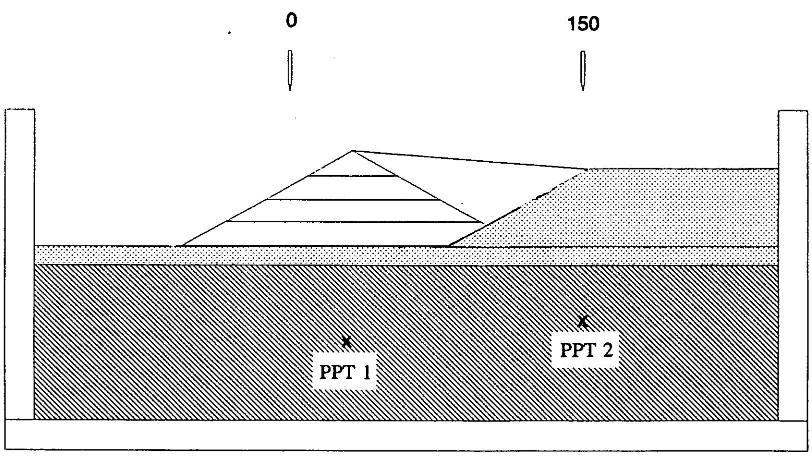
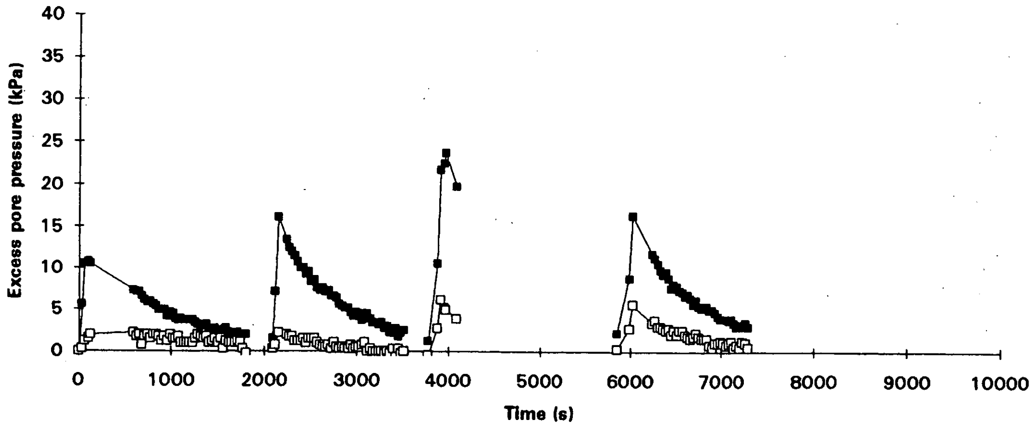


FIGURE 7 Widening by gap method.



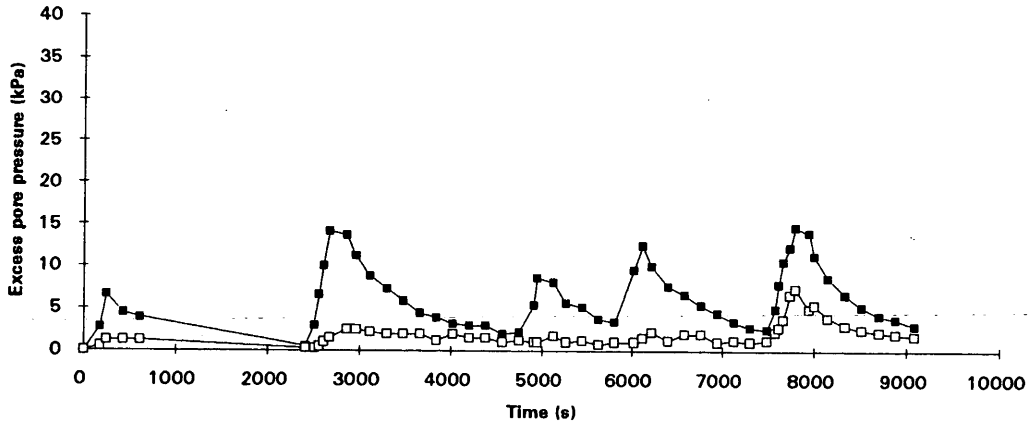


FIGURE 8 Course of excess pore pressure during widening, each peak representing a new layer (100 percent consolidation): horizontal method (*top*) gap method (*bottom.*)

located under the new embankment and PPT 2 was located under the slope of the existing embankment. This can be seen by noticing that the excess pore pressures of PPT 2 increased most when the gap was filled. The horizontal method causes larger peaks in the pore water pressure than the gap method, probably because more sand is added in a layer.

The displacements of the nodes of the grid on the clay layer and the displacements of the beads in the existing embankment can be measured with the help of image processing. Figure 9 presents the displacement fields of two tests visualized by processing the grid on the clay layer of two test stages and by improving the visibility of the beads in the embankment by image processing. From these tests two main differences can be observed:

- In addition to vertical displacements, the horizontal method caused more horizontal displacements, whereas the gap-method caused mainly vertical displacements. These differences in deformations could be seen particularly in the clay layer.
- The difference between vertical displacements at the toe of the existing embankment and those more to the center was much larger for the horizontal method than for the gap method. From this phenomenon a mechanism can be deduced that can cause horizontal cracks in the asphalt, as shown in Figure 10.

Both widening methods result in approximately the same loading conditions. The difference in deformation can be caused by several phenomena. With the gap method the new embankment has a potential failure mechanism that counteracts horizontal deformation of the existing embankment. Furthermore the same amount of sand is supplied over a larger time interval, so a more stable behavior can be expected because of lower excess pore water pressure. A more specific test program must be carried out to further investigate the influence of these and other factors.

CONCLUSIONS

The embankment testing produced results that came close to what was expected. The soil collapsed according to a slip circle and the safety factor was close to 1.

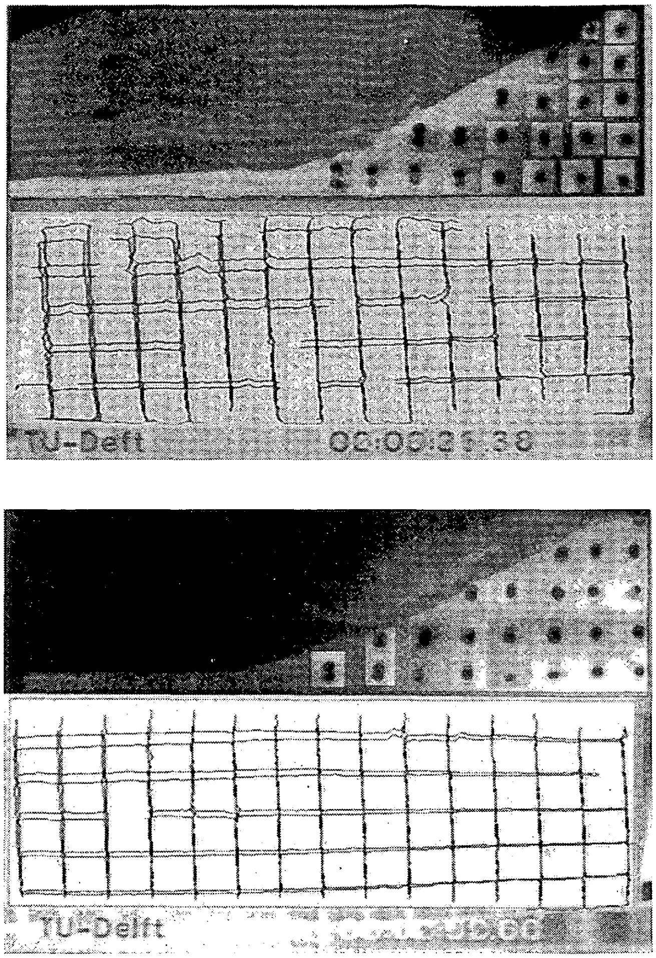


FIGURE 9 Visualized displacement fields after widening and consolidation (grid size 10 mm): horizontal method (*top*), gap method (*bottom*).

The location of the new embankment as constructed for the gap method was important. When there was a large overlap between the two embankments, both the existing embankment and the new embankment did not collapse if the critical height for normally consolidated clay was reached. If the new embankment was constructed at some distance from the existing embankment, the new embankment collapsed, but this had no significant consequences for the existing embankment.

The differences in deformations caused by the two widening methods were not great, but differences could still be observed. In addition to vertical displacements, the horizontal method also caused horizontal displacements. The gap method caused mainly vertical displacements. The difference between vertical displacements at the toe of the existing embankment and those more to the center was much larger for the horizontal method than for the gap method.

Kaolin clay is convenient in centrifuge tests because the consolidation time is short. On the other hand it is not a typical Dutch clay. Therefore a test program is planned to investigate the behavior of a more natural clay type.

Much attention has been given to techniques for preparing reproducible samples. Very good reproducible clay samples could be

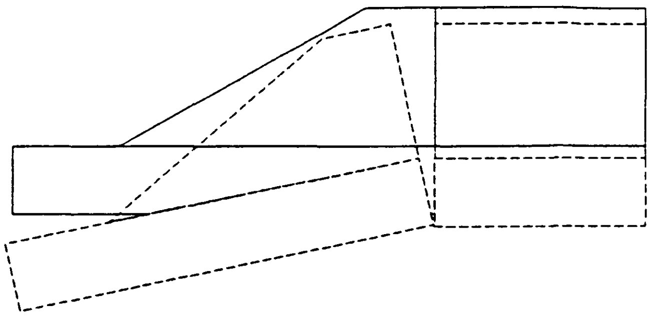


FIGURE 10 Schematic diagram of assumed mechanism that causes cracks in pavement if horizontal widening method is applied.

prepared with the new mixing method of powder and water and the in-flight consolidation of the slurry.

Because of the small size of the samples the centrifuge was flexible in operation and tests could be performed in a short time after the idea was developed. Advanced tests could be performed in flight using the most up-to-date electronics, measuring techniques, and miniature devices. The disadvantage of a small centrifuge is the limitation in sensors, which could be compensated for by using image-processing techniques.

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