Rainfall-induced collapse of old railway embankments in Norway

Influence des precipitations sur l'instabilité d'anciens remblais ferroviaires en Norvège

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ABSTRACT: During the second half of year 2011 heavy rainfall caused dramatic damage on railway foundations in Southern Norway. Most of the railway foundations affected are old, generally constructed between 1850 and 1950 at a time when construction work was done manually, and soil materials from cuts in local natural deposits were utilized for construction of nearby embankments. Quality of culverts and embankments therefore does not correspond to modern construction standards. As a consequence the embankments do not perform well during intense and prolonged rainfall as demonstrated in the fall of 2011. In some cases, low capacity of old culverts caused rise in water levels upstream of embankments, followed by internal erosion and ended in complete destruction of embankments. However, the collapse of several embankments was not related to this factor. The geotechnical behaviour of some of the collapsed embankments, constructed of sandy, silty and clayey material was studied, and the results for one of these are presented in this paper. Unsaturated flow properties were taken into account to explain the behaviour. .

RÉSUMÉ: Au cours de la seconde moitié de l'année 2011, suite à d'intenses précipitations, un certain nombre de voies ferrées et leurs fondations ont été endommagées dans le Sud de la Norvège. La plupart des ouvrages touchés étaient anciens et avaient été construits dans les années 1850-1950, à une époque où les travaux se faisaient à la main et où les matériaux employés pour la construction des remblais étaient prélevés sur des chantiers à proximité. La qualité de ces ouvrages ne correspond donc pas aux standards actuels de construction. Par conséquent, ils ne sont pas toujours en mesure de résister à de fortes et longues périodes de pluie, comme cela s'est démontré à l'automne 2011. Dans certains cas, la faible capacité des drains a entraîné la montée du niveau d'eau en amont des digues, provoquant l'accélération de l'érosion interne et, au final, la destruction complète de la structure. Dans certains cas néanmoins, le phénomène s'explique par d'autres causes. Le comportement géotechnique de certains des ouvrages ayant été détruits, lesquels sont généralement construits sur des sols sableux, silteux et argileux, a été étudié et est présenté dans cet article. Les écoulements non saturés ont été pris en compte pour expliquer les phénomènes observés.

KEYWORDS: railway, stability, embankment, culvert, rainfall, retention curve, permeability, grain size distribution

1 INTRODUCTION

The railway infrastructure in Southern Norway suffered serious damage during the second half of 2011. The damages, often leading to complete destruction of sections of the railway, were caused by prolonged and intense rainfall. Monthly rainfall of >150 % of normal values were observed, with estimated periods of 30-50 years. NGI assisted on a number of occasions where railroad infrastructure was damaged. Cases were distributed over a large geographical area and on most major railway lines in Southern Norway. In this paper, typical damages are discussed. A case study of a failed railway embankment is also presented, with special emphasis on the geotechnical behaviour.

2 OLD RAILWAYS AND DAMAGES

2.1 *Some features of existing railway infrastructure*

Railway lines constructed between 1850 and 1950 constitute the major part of present railway infrastructure in Norway. Some modernization as widening of embankments has been done, some culverts have been renovated, new ballast types introduced, however, much of the original substructure, 50-150 years old, remains more or less unaltered. Documentation from the construction phase shows that the principal of mass balance along the railway was used. Manual labour and mass transport by wheel barrows prevented long distance transport, and prohibited the use of materials from e.g. remote stone quarries. Soil from cuts was placed in nearby embankments; hence, materials as clay, silt and sand are today encountered in the railway embankments. Culverts passing under the railway were typically constructed by dry masonry of rectangular hewn blocks of stone. Some culverts have been modernized as part of maintenance or after damage, often by inserting plastic pipes into old stone culverts. This reduces the cross section, and flow capacity may be reduced, although smoother surface partly compensates for reduced cross section. Inspection however shows that even after operating times of >100 years many culverts are in surprisingly good condition.

2.2 *Types of damages*

In the following description of damages, direct hit on the infrastructure from landslides initiating outside the railway is excluded. The discussion is limited to damages on railway infrastructure due to extraordinary rainfall in the second half of year 2011. Observed damages are categorized in a few main groups: 1. Damages related to culverts.2. Damages related to flooding. 3. Damages related to embankment slope failure.

2.3 *Damages related to culverts*

Embankment collapses caused by inadequate performance of the culverts is a well-known phenomenon along existing railways. Depending on the soil type in the embankments, complete destruction of embankments may occur surprisingly quickly. In pioneering days of railway engineering, culverts were not designed by detailed analysis of discharge from upstream catchments (although planning was thorough, including years of field surveying and observations). However, over long time periods and including possible climatic change with increased rainfall, it is no surprise that the flow capacity of the culverts may be exceeded from time to time. Human activity, as urban development or construction of highways, may also result in changed drainage patterns along the railway line, increased discharge and reduced concentration time for the catchment. ”Wear and tear” of the constructions and insufficient maintenance may reduce flow capacity of culverts. Maintenance may fail to detect damage or blockage of inlet or outlet, or collapse of culverts inside embankments. One problem has been that culverts are not extended when embankments are widened, which may result in burying of inlet or outlet.

In 2011 damage was frequently caused by flash floods following intense short-duraion rainfall. High discharge may result in upstream damming of water due to the culvert being unable to transport the discharge from the catchment, unless the water finds alternative ways underneath or through the embankment (which in turn destabilized several embankments constructed of sand during the same period). Damming of water will increase pore-water pressures in the embankment and lead to collapse of a construction which needs drained conditions to remain stable. Overtopping of embankments is particularly disastrous, especially for embankments constructed of materials that are easily eroded, as sand and silt. Embankments may experience rapid and total destruction under such conditions. A photo showing an example of complete destruction of the embankment around a culvert is shown in Fig. 1. Note that the embankment is mainly constructed of relatively fine, sandy soil.

Figure 1. Example of total destruction of embankment around culvert near Ål, Bergensbanen railway line (Oslo to Bergen).

Settlements of the underground due to the weight of the embankment may be considerable on soft marine clay, and also results in deformation of the culvert. Settlements increase under the centre, and decrease towards the foot of the embankment. Horizontal sliding of culverts may also be caused by horizontal soil pressures within the embankment. Displacements result in the opening of gaps between stone blocks. Sprinkling of soil from the embankment may result in cavities in the embankment. Gaps may also result in water leaving the culvert, finding new flow paths through the embankment, causing internal erosion. Large deformations may lead to collapse and internal blocking of the culvert. Vegetation transported during flooding may block the inlet of culverts temporarily, which may not easily be detected during an intense rainstorm. Landslides in the side terrain can block the culvert and cause upstream damming.

For flash-flood events it is a problem that even regular and frequent inspection of the railway during a critical situation may be insufficient to detect incipient collapse of embankments. Collapse of the embankment around a culvert may occur between two consecutive inspections due to short-term intense scours. For small catchments concentration times are short, and the distance between existing meteorological stations does not give sufficient information to forecast flash- flood events along the railway lines (even when weather radar images are used as supplement). In some cases, trains, unable to stop when a collapsed section of the railway line was encountered without any warning, have spectacularly passed the collapsed section of the embankment on rails hanging in the air, as a suspended bridge. In other cases, suspected embankment collapses have been reported by the engine driver, who noticed unusual behaviour of the train. The weight of the train then was the remaining load necessary to initiate the collapse, which may have occurred as rapid liquefaction of saturated soil volumes.

Improved maintenance, redesign and reconstruction of culverts may reduce problems in the future. However, the high number of culverts lines (tens of thousands) indicates that similar collapses of embankments may still be a problem in the future. Improved design of culverts with built-in safeguards (increased cross section, double pipelines etc.) is possible, but costly judged from normal maintenance budgets. Modernization normally is restricted to already known problem areas. This will keep existing culverts mainly unaltered and still contributing to a high future risk.

2.4 *Damage related to flooding*

A second type of damages is caused by flooding in large rivers and lakes along the railway. Settlements, local slope failures of embankments, erosion along embankments and deposition of fines are typical results of general water rise in rivers or lakes. Slopes typically collapse when external water levels normalize.

During 2011 flooding was primarily a problem along the Dovre line, the main railway line between Oslo and Trondheim, and traffic was cut in periods. Due to the nature of flooding in large rivers and lakes, these situations generally are less dramatic than sudden destruction of embankments at culverts. Water levels from regional flooding normally rise comparatively slowly (when compared to flash floods in small catchments), which allows evaluation of the situation as it develops. Railway lines are normally resilient to such events, and complete collapse will normally not occur. For regional flooding the situation may be monitored as flooding develops, and associated risk for train traffic be evaluated. The Norwegian national system for flood warnings is well developed, and flooding in large rivers and lakes should come as no surprise. Based on regional warnings and weather forecasts mitigating actions may ideally be well planned (e.g. reduced speed, temporary closure of train traffic). The National Railroad Administration also has introduced three alert levels for these situations, based on weather forecasts.

2.5 *Damages related to embankment slope failure*

A third type of damage relates to slope failures in embankments. Some embankments collapsed due to increased supply of water in dikes upstream of the embankment. However, several embankments collapsed where there were no culverts, no dammed water upstream of the embankment, and where no flooding occurred. Some collapses appeared rather enigmatic at the first glance, and are interesting from a geotechnical point of view. One slope failure occurred on an embankment elevated about 5-6 m above a flat terrain, while another occurred on an 8-10 m high fill across a ravine. For these embankments water should ideally not be able to invade the construction, however, this is exactly what happened. One case is discussed in more detail in this paper.

3 CASE: TOMTER EMBANKMENT FAILURE

A slope failure at a railway embankment at Tomter occurred on 23rd December 2011. The line was not physically cut off, but train traffic was stopped until inspection by geotechnicians from NGI was made the following day. A cross section is shown in Fig. 2. Field survey was somewhat hindered by low temperatures and a thin frozen crust that had developed through the preceding night. It was found that the embankment consisted of a bottom layer of clay on top of the natural terrain (marine clay), followed by a layer with high sand and silt content. Above this layer there was a 1 m thick layer of sand and gravel, added in a general uplift of the track around 1950-60, and at the top crushed rock ballast. In spite of the elevation above the surrounding terrain, the sandy/silty layer was observed to be very moist, and appeared almost liquefied. The water content w of a bag sample was measured to 17.5 %. In situ saturation rate of the sandy/silty layer may not be determined from a bag sample (in situ density is unknown and water is lost during sampling), but this indicates that the sandy/silty layer may in fact have been close to full saturation prior to the slope failure.

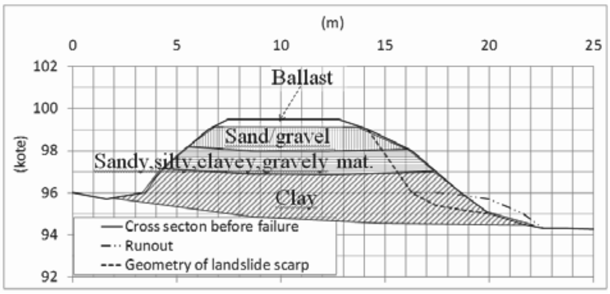

Figure 2. Cross section of failed embankment at Tomter, Østfold county railway line. Geometry of slope failure 23rd December 2011 is indicated. Natural soil below embankment is marine clay.

Results from grain size distribution (GSD) analysis of the sample are summarized in Table 1 and Fig. 3. The moist layer described in field as a sandy/silty layer is characterized as sandy, silty, gravely and clayey material, according to terminology and grain size limits defined in Norwegian Geotechnical Association (1982). The soil is well graded.

Table 1. Results from grain size distribution analysis of bag sample

Parameter	Value
Gradation number $C_u = D_{60}/D_{10}$ (-)101.1	101.1
Clay content D < 0.002 mm (%)	6.9
Silt content 0.002 < D < 0.006 mm (%)	21.4
Sand content 0.006 mm < D < 2 mm (%)	54.2
Gravel 2 mm < D < 60 mm (%)	17.5

An empirical curve for the grain GSD is also shown in Fig. 3. The curve was fitted by using a five parameter equation for unimodal GSD (Fredlund et al. 2000), see Eq. 1. In Eq. 1, the percentage of particles Pp passing a certain sieve size is given as a function of the particle diameter D (mm). The parameter a_{gr} is related to the breaking point of the curve, n_{gr} is related to the steep part of the curve, m_{gr} is related to the shape of the curve in the fines region, d_r is related to the fines content and d_m is the minimum allowable particle size. The value of d_m was chosen based on the grain size data. The other parameters are result of statistical optimization. For the resulting curve the R^2 value is 99.15%. Final parameters are shown in Table 2.

Also shown in Fig. 3 is the logarithmic PDF (probability density function) for the sample, which is the result of differentiating the GSD-curve. The PDF will correctly represent the most frequent particle size when first taking the logarithm of the particle size, see Eq. 2 (Fredlund et al. 2000), in which $P_l(D)$ is the logarithmic PDF. For the analyzed sample the most frequent particle sizes are found in the sandy fraction, with a peak at 0.3-0.4 mm. This corresponds with the laboratory description of the soil, where the first adjective ("sandy") nominates the largest mass fraction.

$$Pp(D) = \frac{1}{\ln\left[\exp(1) + \left(\frac{a_{gr}}{D}\right)^{n_{gr}}\right]^{m_{gr}}} \left\{1 - \left[\frac{\ln\left(1 + \frac{d_{rgr}}{D}\right)}{\left(1 + \frac{d_{rgr}}{d_m}\right)}\right]^7\right\} \tag{1}$$

$$P_l(D) = \frac{dP_p}{d\log(D)} \tag{2}$$

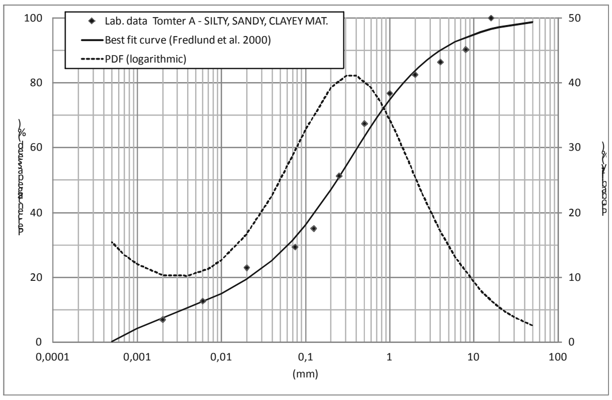

Figure 3. Results from laboratory GSD analysis, empirical GSD function and logarithmic PDF (Fredlund et al. 2000).

Table 2. Parameters for empirical GSD curve (Fredlund et al. 2000).

Parameter	*Sample Tomter A*
a_{gr} (-)	0.6133
n_{gr} (-)	0.8357
m_{gr} (-)	1.4909
d_{rgr} (-)	0.7612
d_m (mm)	0.0005

4 ANALYSIS OF EMBANKMENT FAILURE

The railway embankment that collapsed at Tomter on 23rd December 2011 is used to illustrate the geotechnical behaviour of old railway embankments. The seepage module Seep/w of the geotechnical software Geo-Studio 2007 (Geo-Slope International 2007) was used for flow analysis of the embankment. The routine in Seep/w for predicting the water retention curve from GSD data (Aubertin et al. 2003) was used for layer B. For layers A and C, ad hoc curves are used to represent typical properties for these layers and are not discussed further here. Hydraulic conductivity functions and saturated permeability for layers A, B and C are shown in Fig. 3 and Table 3, respectively. The top layer D (crushed rock ballast) is assumed very permeable and completely drained, and is excluded from the seepage analysis.

The hydraulic conductivity curves show the well-known effect that less permeable clay (when saturated) is more permeable than coarse-grained soils for high matric suction.

Table 3. Saturated permeability used in seepage calculation

Parameter	Layer A: clay	Layer B: Sandy, silty, gravely, clayey mat.	Layer C: sand/gravel
K_{sat} (m/s)	10^{-9}	10^{-7}	10^{-5}

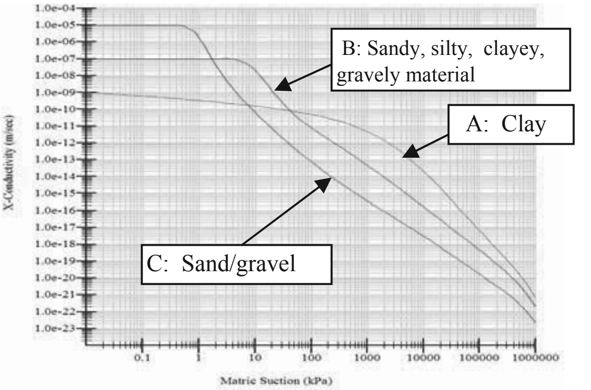

Figure 4. Hydraulic conductivity curves used in seepage analysis for layers A , B and C.

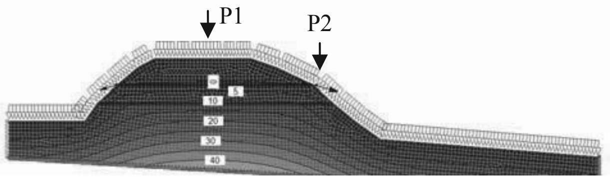

Figure 5. Example of flow analysis. Predominantly positive pore-water pressures. Position of profiles presented in Fig. 6 is indicated.

To get an idea of the range of pore-water pressures resulting from infiltration seepage analyses were made for varying values of constant infiltration. Annual rainfall in the region corresponds to ca. 2.5E-08 m/sec, ~800 mm/year (Norwegian Meteorological Institute 2011). Runoff will result in infiltration being smaller than the rainfall. Constant infiltration on the surfaces of the embankment has been varied between 1.25E-09 and 2.5e-08 m/sec. Results are shown in Fig. 5 for two profiles, one at the centre and one at the edge of the embankment. Applied infiltration rates are equal on top of the embankment and on the slopes. Subsequent analyses reducing infiltration rates on the slopes did not result in substantially different results. Seepage boundaries are used to find the extension of seepage zones at the bottom of the slopes. From the seepage analyses, it appears that even low infiltration rates produce positive pore-water pressures in layers A and B. The pore-water pressures at P1 at the centre of the embankment vary between 80 and 90 % of hydrostatic pore-water pressure for the chosen range of infiltration rates. For P2 at the edge of the embankment the pore-water pressures vary between 70 and 75 % of hydrostatic pore-water pressure.

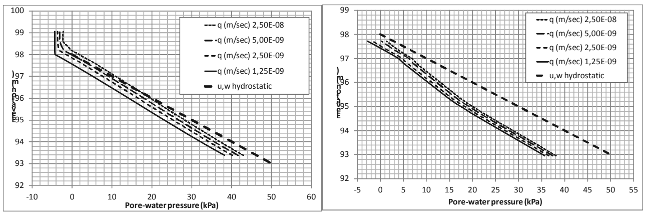

Figure 6. Calculated and hydrostatic pore-water pressure vs. depth for profile P1 (left) and P2 (right) as indicated in Fig. 5.

For positive pore-water pressures, Mohr-Coulomb friction parameters and the effective stress principal (Terzaghi 1943) may be used. Stability calculations for the embankment with positive pore-water pressures from top of layer B result in critical values the safety factor (~1.0) for realistic choices of shear strength parameters. In Fig. 7 results are shown for 75-90% of hydrostatic pore-water pressure distribution from top of layer B. It is underlined that strength parameters were not measured. Stability analyses were done by the limit equilibrium method using the software package GeoSuite Toolbox (ViaNova Systems 2007).

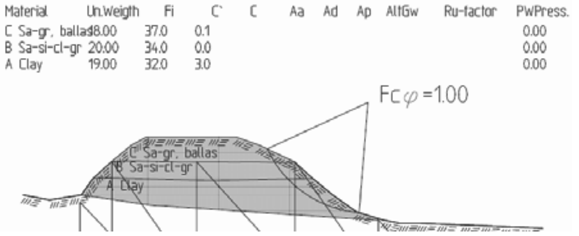

Figure 7. Stability calculation. 75-90% of hydrostatic pore-water pressure from top of layer B. Shear strength parameters shown at top.

The soils in the embankment prevent water from being drained from the construction. The situation probably varies through the year, and factors not taken into account in the analyses may improve or worsen the situation. Additional water may be transported along the embankment from other areas, on top of the clay layer which may be deformed by settlements, or by capillary suction in layer B. The particular worry for this kind of slope stability problem is that there are normally not clear any precursors to the failure and destabilization of the embankment is not easily observed.

5 CONCLUSIONS

A: Under-dimensioned, damaged or blocked culverts may result in rapid destruction of old railway embankments during flash-floods, which may occur more frequent in the future as a result of climate change. The problem may be addressed by improved maintenance/inspection, or by redesign/modernization of the drainage systems. B: Slope failures may occur in old embankments constructed of clay, silt, sand and gravel without clear precursors to failures. Analyses indicate that slope stability may be critical also without unusual weather conditions. There seems to be a need for improved research on the geotechnical behaviour of such embankments.

6 ACKNOWLEDGEMENTS

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