Long-Term Behavior of Flexible Large-Span Culverts

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Two large-span flexible steel culverts in Norway were instrumented for monitoring long-term behavior. The first structure was a pipe arch with a span of 7.81 m completed in 1982, and the second was a horizontal ellipse with a span of 10.78 m completed in 1985. Both structures are backfilled with high-quality, well-graded dense gravel and sand. The main influence on the long-term effects is likely to be environmental factors such as seasonal temperature and moisture variations. In Norway, the winter is very cold and seasonal temperature changes are great. Hydraulic earth pressure cells of the Glötzl-type are used on both structures, and thermistors are used to measure temperature variations. In addition, strain gauges are mounted on the horizontal ellipse to measure stress changes in the steel structure on a long-term basis. The long-term observation of the flexible steel culverts in this study shows that they undergo changes in earth pressure distribution and structural response as time progresses after construction. On both structures, the horizontal earth pressure at the springline has increased to values somewhat above the overburden pressure. The measured thrust force in the steel on the horizontal ellipse increases considerably with time. Although the measured vertical earth pressure over the top of the structure is less than the overburden, the measured thrust stress indicates negative arching for the structure as a whole.

Long-span flexible steel culverts are increasingly being used in highway projects in Norway as alternative solutions to bridges and culverts and for snow avalanche protection. The construction period can be short, and the structures have both technical and economical advantages.

The idea of using long-span flexible culverts is relatively new. Several approaches have been suggested for the design of such structures, but no exact theoretical analysis is available. Both analytical and experimental investigations have focused predominantly on the soil-structure interaction between the culvert and the surrounding soil as a result of backfilling and live load at the end of construction. But it is recognized that flexible culverts often undergo changes in deformation and structural response as time progresses after installation.

Spangler (*1*) introduced the deflection lag factor in the Iowa formula for computing deflection of flexible pipe culverts. The deflection lag factor is used to account for the continued yielding of the soil at the sides of the pipe in response to the horizontal pressures over a considerable period of time after the maximum vertical load has developed. The deflection lag is said to be analogous to the continued settling of structures resting on earth foundations (consolidation) (*1*). The deflection lag factor has been observed to range upward toward a value of 2.0 (*2*).

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According to classical settlement theory (*3*), well-graded dense sand and gravel permit very little residual deflection, although a loosely placed cohesive soil may induce a relatively large deflection lag.

On large-span culverts, long-term deflection increases of about 50 percent have been observed (*4*) and failure has occurred after 10 years of service (*5*).

The long-term effects, attributed to consolidation of the soil mass, are influenced by environmental factors such as seasonal changes, in moisture content and temperature. Within the last decade, modern analysis procedures (*6–8*) have made great advancements in predicting realistic capabilities for the design/analysis of buried culverts. However, attention has been limited to analyzing the construction sequence without considering long-term effects.

Long-term experimental information in the literature is limited, but some field studies have been reported (*9–13*). Centrifuge modeling is used to study viscous consolidation, one of the long-term effects (*14*).

Two large-span flexible steel culverts in Norway are instrumented for monitoring long-term behavior. Both structures are backfilled with high-quality, well-graded dense gravel and sand.

The main influence on the long-term effects is likely to be environmental factors, such as seasonal temperature and moisture variations. Norway is very cold in the winter and has great seasonal temperature changes.

The first structure was a pipe arch completed in 1982, and the second was a horizontal ellipse completed in 1985. Both structures have longitudinal stiffeners of reinforced concrete.

Hydraulic earth pressure cells of the Glötzl type are used to measure the earth pressure distribution on both structures, and thermistors are used to measure temperature variations. In addition, strain gauges are mounted on the horizontal ellipse to measure stress changes in the steel structure.

TOLPINRUD STRUCTURE

The Tolpinrud structure, located at Hønefoss, about 60 km north of Oslo, is a pipe arch with a span of 7.81 m and a rise of 6.92 m (Figure 1). A cross section is shown in Figure 2. The structure is constructed of steel plates with corrugations 200 by 55 mm and thickness 6.8 mm (1 gauge). The structure, which serves as a railroad tunnel under a main road, is 106 m long. The first super-span structure in Norway, it was completed in 1982. The savings compared to the cost of a bridge was about 25 percent, or NOK 1.5 million.

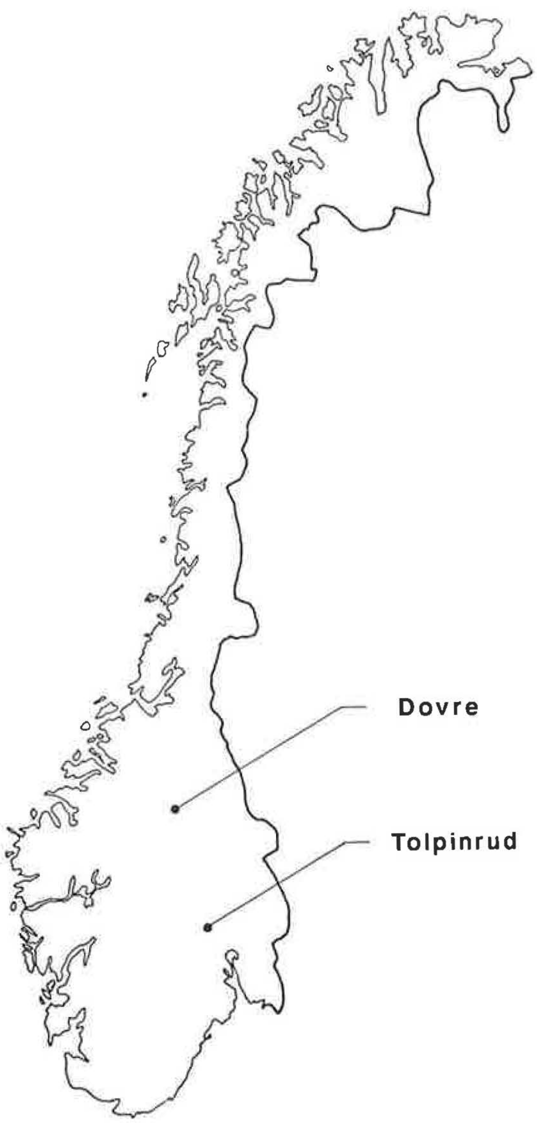


FIGURE 1 Location of the Tolpinrud and Dovre structures.

The backfill consists of gravel and sand compacted to minimum 97 percent Standard Proctor. The extent of the backfill is shown in Figure 2. The backfill was placed in 20-cm-thick layers and compacted with a 1100-kg vibratory roller and a 12-t bulldozer. The depth of cover over the crown varied from 1.1 m to 1.6 m. The in situ soil is a medium stiff clay with undrained shear strength 40 to 80 kN/m^2.

INSTRUMENTATION ON TOLPINRUD STRUCTURE

Earth pressure cells of the Glötzl type were mounted on the structure at two sections, one 25 m from the northern end and the other 50 m from the northern end. Six earth pressure cells were used at each section. The location of the earth pressure cells is shown in Figure 2.

Four of the earth pressure cells were bolted on the steel structure using specially constructed brackets. A bracket with an earth pressure cell is shown in Figure 3. The brackets have the same corrugation and radius as the culvert structure.

One cell was placed horizontally in the sand under the culvert, and one cell was placed vertically in the backfill 0.5 m from the thrust beam to measure the horizontal earth pressure.

The earth pressure cells are 30 by 40 by 0.5 cm. The brackets are 60 by 80 cm.

The working principle of the Glötzl earth pressure cell is shown in Figure 4. Calibration of the cells was performed by the manufacturer and was found to agree well with calibration checks in our laboratory. Calibration of the cells with temperature variations from +20°C to −30°C was also performed in our laboratory.

With this cell the pressure shown on the gauge during circulation of oil is related to the earth pressure, σ, by the expression:

$$p_A + p_B = p_O + A \cdot \sigma + p_C \tag{1}$$

where

p_A = the pressure given by the cell pressure gauge,
p_B = the difference between the level of the cell and pump,
p_O = the pressure required to cause circulation of oil,
A = the cell action factor, and
p_C = a pressure term due to temperature change.

Woodford and Skipp (*15*) found the action factor A to be 0.96 in a field loading condition compared with results from a large test chamber. Penman and Charles (*16*) used a 1-m diameter odometer based on a design by Kjaernsli and Sande (*17*) to test the Glötzl earth pressure cells. An action factor of 0.943 was found.

Thermistors were placed near each earth pressure cell and also elsewhere in the backfill to give data for temperature corrections and freezing depths.

Deformations of the steel structure were also measured during construction and on a long-term basis. Deformations were measured with tape. Further details of the instrumentation are given by Knutson (*18*) Johansen (*19*).

OBSERVED MEASUREMENTS AT TOLPINRUD

Earth pressure readings were taken from the beginning of construction in 1981 until August 1988 (Figure 5). The vertical overburden pressure at cell level and the temperature measurements near each cell are also shown in the figures.

The measured earth pressure at the crown is about equal to the vertical overburden pressure and shows small variations with time (Figure 5a).

The measured lateral earth pressure at the springline is about 50 percent of the vertical overburden pressure at this level at the end of construction (Figure 5b). After about 1 year, the lateral earth pressure increased to about 100 percent of the vertical overburden pressure. A further moderate increase is indicated during the following years.

The measured earth pressure at the haunch (Figure 5c) is lower than the measured lateral earth pressure at the springline. Earth pressure distribution from the ring-compression theory (*20*) predicts greatest earth pressure at the haunch.

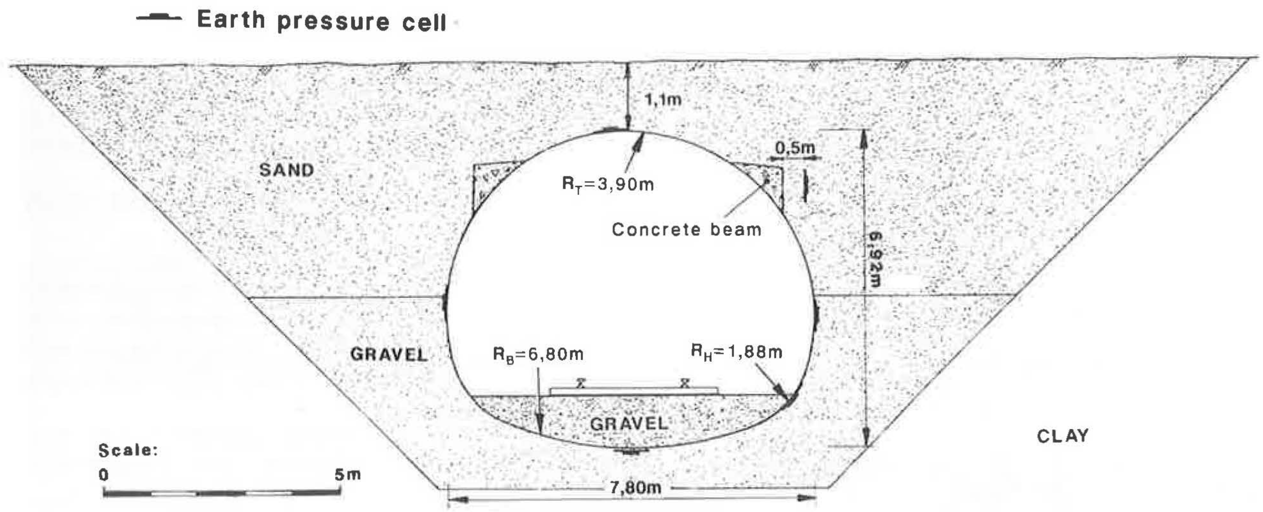


FIGURE 2 Geometry of instrumented cross section with location of the earth pressure cells (Tolpinrud).

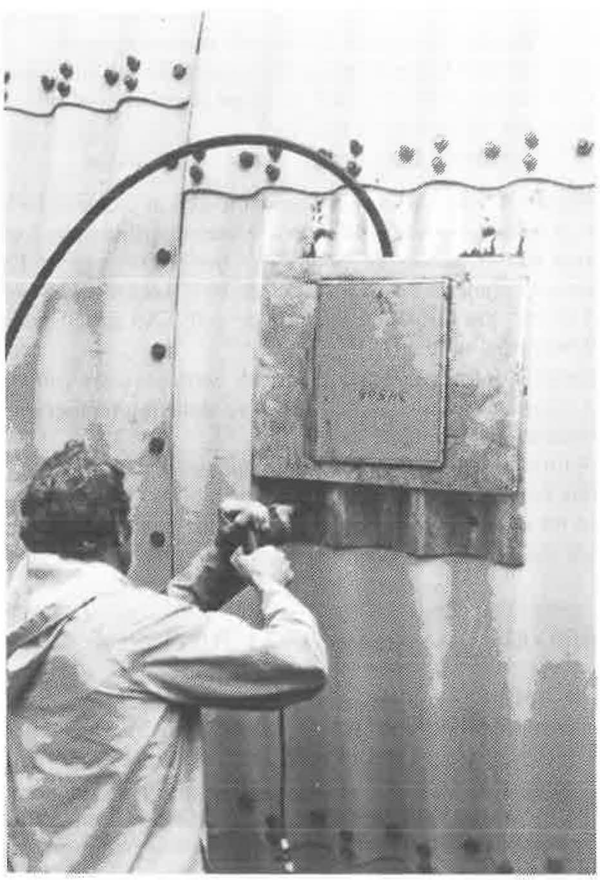


FIGURE 3 Earth pressure cell with bracket on the structure.

The calculated earth pressure at the haunch (corner) according to the earth pressure distribution on pipe arches from the ring-compression theory (*20*) is:

$$p_H = p_V \cdot R_T/R_H = 41 \text{ kN/m}^2 \quad (2)$$

where $p_V = \gamma H = 19.8$ kN/m² is the vertical overburden at the top of the structure, $R_T = 3.9$ m is the radius at the crown, and $R_H = 1.88$ m is the radius at the haunch.

In Figure 5d, the measured earth pressure at the bottom of the structure is shown. The earth pressure is decreasing with time.

The measured lateral earth pressure 0.5 m from the thrust beam is shown in Figure 5e. The measured pressure there is very low.

The earth pressure distribution around the structure at the end of construction and after 18 months is shown in Figure 6.

The observed long-term deformations on the structure are small. The observed downward deformations from February 1983 to November 1986 are shown in Figure 7. The total vertical deformations of the crown are 15 mm (point A). Points B and C indicate that the whole structure settled 10 mm, so that the relative long-term deformation of the crown is only 5 mm. The total outward horizontal displacement at the springline in the same period was less than 15 mm. The reported values are average values from observations at five sections.

DOVRE STRUCTURE

The culvert is located at Dovre, about 350 km north of Oslo (Figure 1). The structure, a horizontal ellipse with a span of 10.78 m, rise of 7.13 m, and total length of 35 m, serves as a road tunnel for Euroroad 6. The depth of cover over the crown is 4.2 m. Built in 1985 in a cut-and-cover operation through a soil ridge, this is the largest long-span flexible steel culvert in Scandinavia.

A cross section of the structure is shown in Figure 8. The structure was built using 7-mm-thick steel plates with corrugations of 200-mm pitch and 55-mm depth. The plates were assembled in the field, using 20-mm-diameter high-strength bolts in 25-mm-diameter holes. There are 15 bolts/m of longitudinal seam.

High-quality well-graded gravel was used for backfilling in a zone extending 6 m out from the springline and 2 m above the crown. The remaining backfill consisted of sandy silt. The

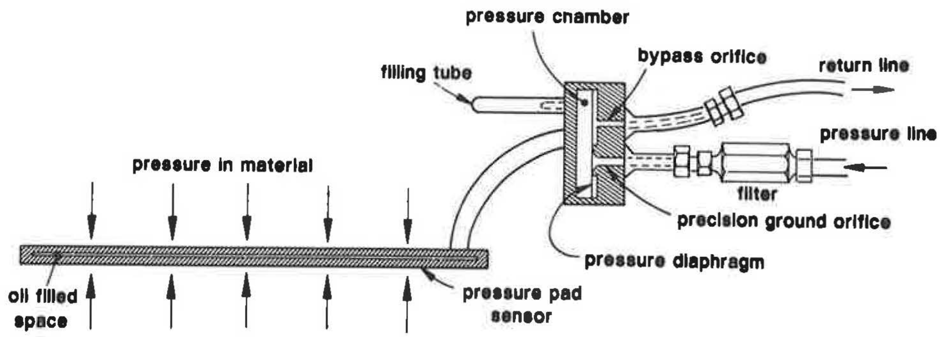


FIGURE 4 The principle of Glötzl earth pressure cell.

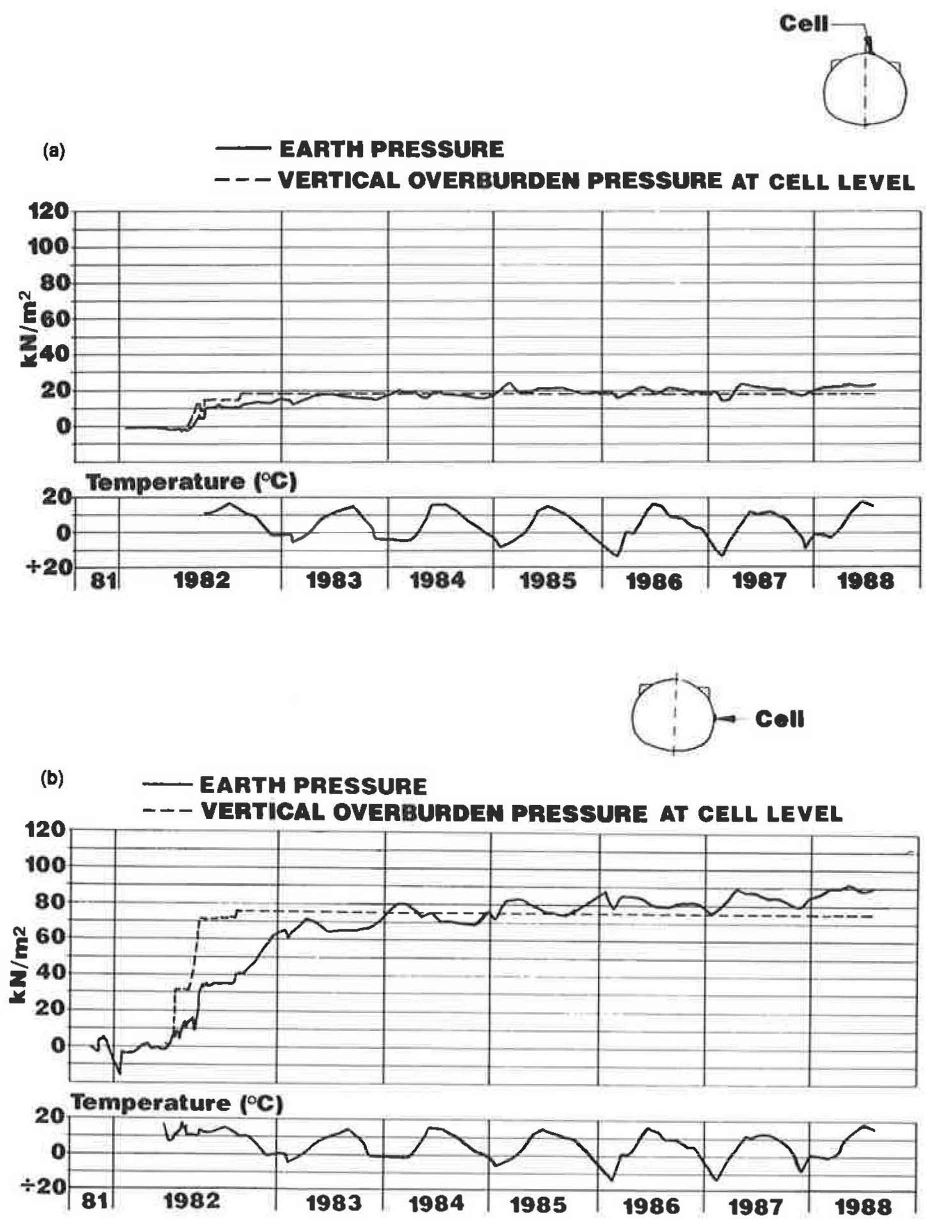


FIGURE 5 Measured earth pressure and temperature (Tolpinrud).

FIGURE 5 *(continued on next page)*

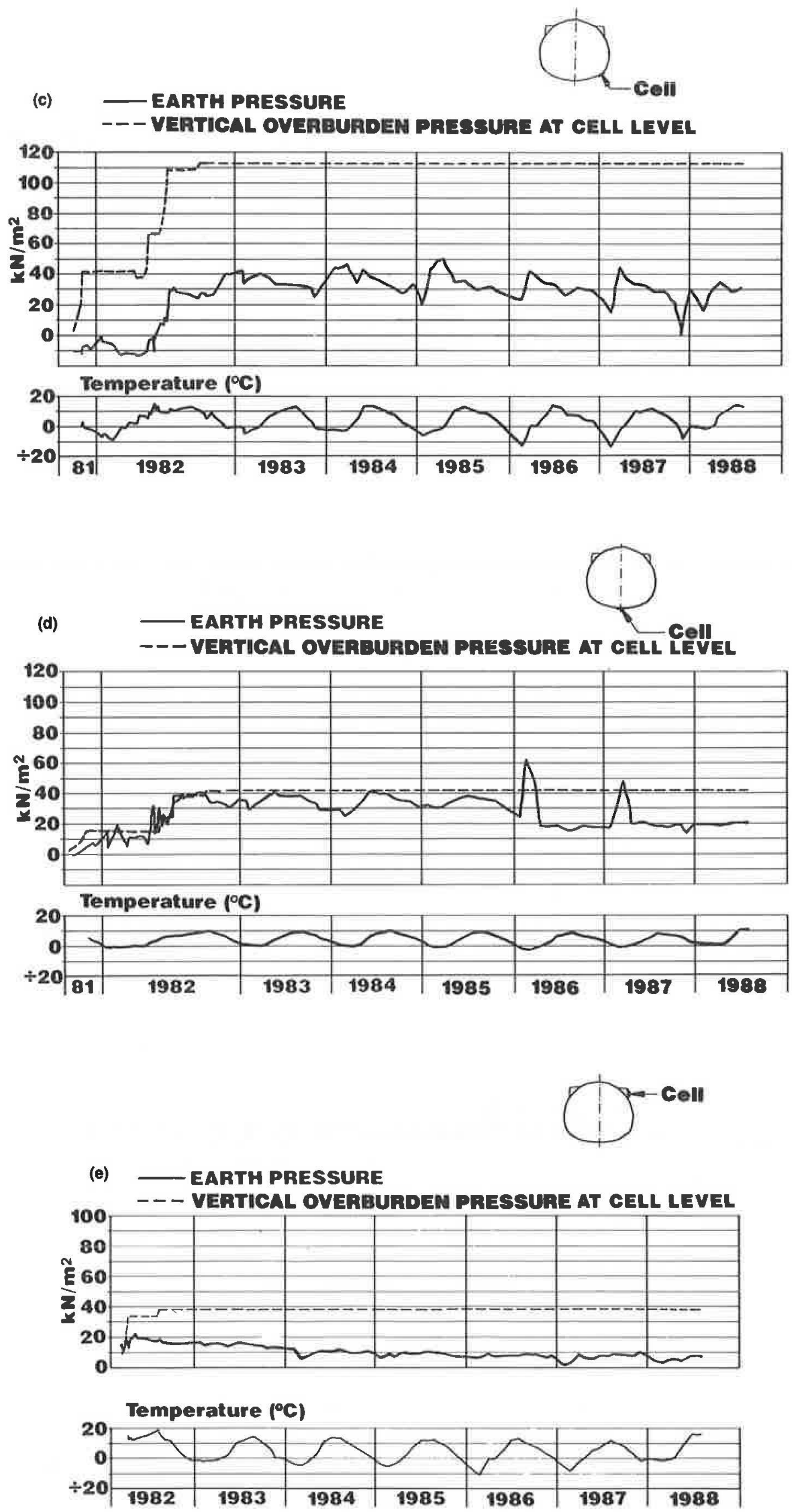


FIGURE 5 *(continued)*

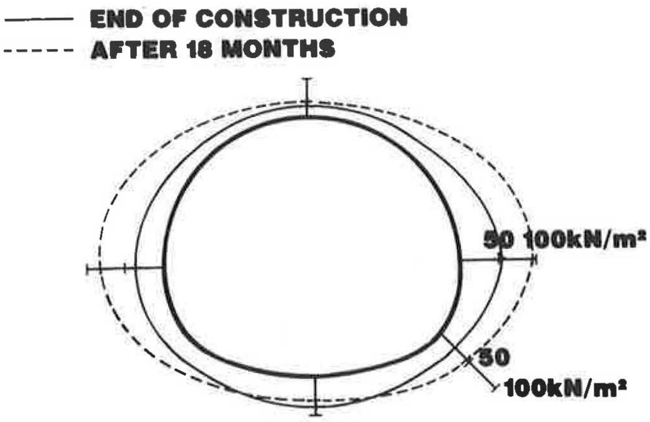


FIGURE 6 Measured earth pressure around the structure (Tolpinrud).

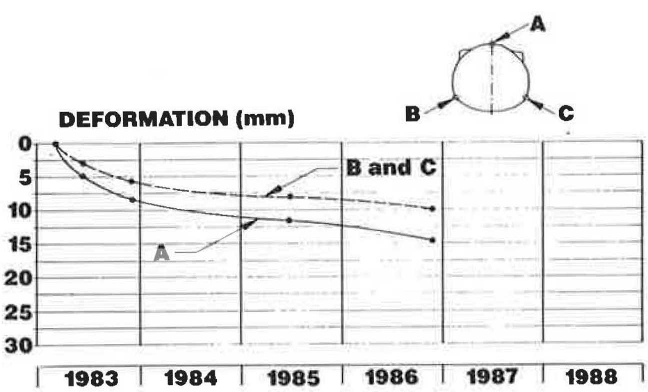


FIGURE 7 Long-term deformations (Tolpinrud).

in situ soil consisted of relatively dense sandy silt. The well-graded gravel was placed in layers of maximum 30 cm and compacted to minimum 97 percent Standard Proctor.

The maximum allowed upward displacement of the crown during placement of backfill was 2 percent of the design height (143 mm). The maximum observed upward displacement when backfilling was 63 mm.

The construction considerations used for long-span flexible steel structures in Norway are given elsewhere (*21*).

INSTRUMENTATION AT DOVRE

Hydraulic earth pressure cells of the Glötzl type, strain gauges, and thermistors were installed at one cross section near the middle of the structure. The geometry of the selected cross section with the location of earth pressure cells and strain gauges is shown in Figure 8.

Eight earth pressure cells were used. Four cells were bolted directly on the steel structure using specially designed brackets of the same type used at Tolpinrud. One cell was placed horizontally in the sand under the structure, two cells were placed horizontally 0.3 m and 1.5 m over the crown to monitor arching effects, and one cell was cast vertically in the concrete on the thrust beam to measure the lateral earth pressure on the beam.

Thermistors were installed near each earth pressure cell to measure the temperature variations in the soil.

Strain gauges were placed at 10 locations inside the steel structure. Two gauges were fitted at each location, one at the top of the corrugation and one at the bottom. This allowed thrust and bending stresses to be determined during backfilling and on a long-term basis. Dummy gauges were installed to provide temperature compensation. Further details of the instrumentation are provided elsewhere (*22,23*).

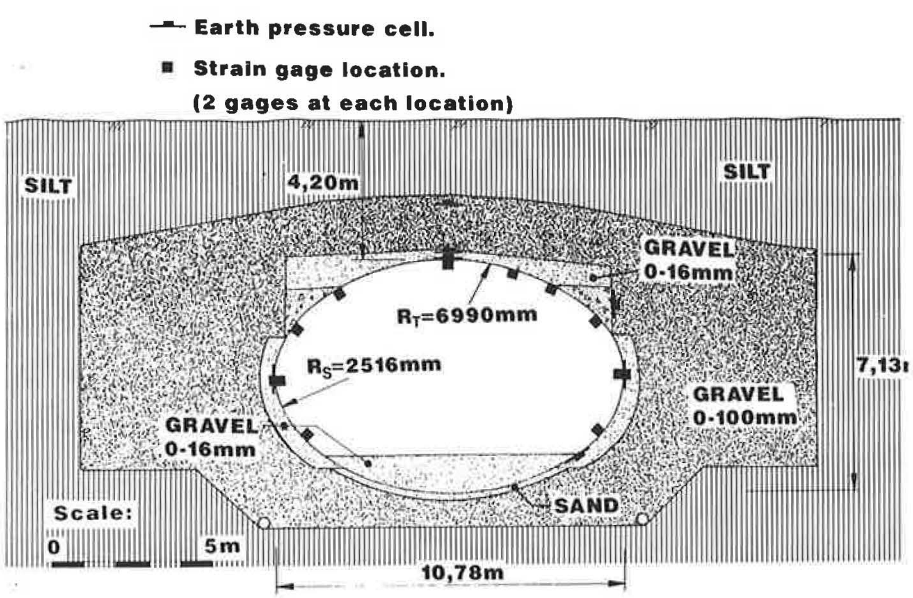


FIGURE 8 Geometry of instrumented cross section with location of the earth pressure cells and strain gauges (Dovre).

OBSERVED MEASUREMENTS AT DOVRE

The maximum observed moment during backfilling was 8 kNm/m, which corresponds to a maximum stress of 77 N/mm². The yield stress in the steel is 235 N/mm². This maximum moment occurred at the crown with backfill at the crown level. The maximum calculated moment according to the design method (*24*) was 19 kNm/m.

The lower and upper boundaries of observed moments from the end of construction in September 1985 until August 1988 are shown in Figure 9. The maximum observed moment in this period was 7.6 kNm/m. The maximum observed moments occur at the crown. The moment distribution is not symmetrical.

The variations in thrust force with time at various locations around the structure are shown in Figure 10. The maximum observed thrust force at the end of construction in September 1985 was 498 kN/m, occurring at the crown. In April 1986 the thrust at the crown had increased to 727 kN/m, and then increased in February 1987 to 860 kN/m, corresponding to a stress of 104 N/mm².

The thrust at the springline was low at the end of construction, but increased considerably with time.

Six different design methods were used to calculate the thrust force in the steel structure. The results are shown below:

Method	*Thrust Force (kN/m)*
Knutson (*18*)	660
Duncan (*24*)	865
Leonards (*25*)	534
Ring-Compression (*20*)	497
AISI (*26*) and AASHTO	588
OHBDC (*27*)	353

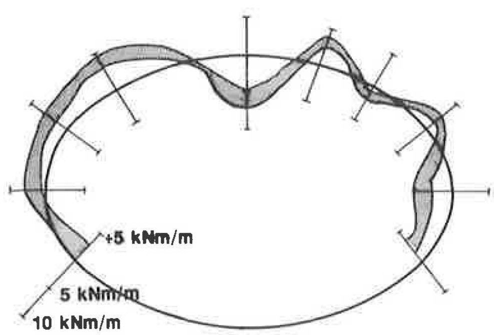


FIGURE 9 Measured moments in the steel structure (Dovre).

The maximum thrust force calculated according to Duncan (*24*) was 865 kN/m, close to the maximum observed thrust force.

The measured lateral earth pressure at springline was almost equal to the vertical overburden pressure at springline elevation at the end of construction, but varies with the temperature over the year as shown in Figure 11a. Today, almost 3 years after construction, the lateral earth pressure has increased and is about 1.3 times the vertical overburden pressure on one side of the structure.

The earth pressure at the lower part of the structure is low, and the annual variations are small, as shown in Figures 11b and 11c. The lateral earth pressure against the thrust beam was 1.55 times the vertical overburden pressure at the end of construction, but varies considerably with time and temperature as shown in Figure 11d.

The earth pressure distribution around the structure at the end of construction and after almost 3 years is shown in Figure 12.

In the cell placed 30 cm over the center of the crown, the measured vertical earth pressure is 30 percent of the overburden pressure as shown in Figure 11(e). The earth pressure on the cells placed 0.3 m and 1.5 m above the crown are shown in Figure 13. The variations of the earth pressure over the observation period are shown. The measured positive arching is nearly constant over the observation period of 3 years. Although the earth pressure over the top of the structure is less than the overburden, the measured thrust stress in the steel indicates negative arching for the structure as a whole. This negative arching occurs because metal culvert structures, although flexible in bending, are stiff in ring compression. The measured distribution of earth pressure also indicates that shear traction is such that the springline thrust exceeds soil column weight over the structure.

The measured long-term deformations in the Dovre structure are small. The maximum horizontal displacement at the springline was 13-mm extension during the observed period.

CONCLUSIONS

The long-term behavior of the two flexible steel structures in this study shows that buried flexible steel culverts undergo changes in earth pressure distribution and structural response as time progresses after construction.

The earth pressure distribution around the pipe arch shows that the earth pressure is greatest at the springline. The lateral

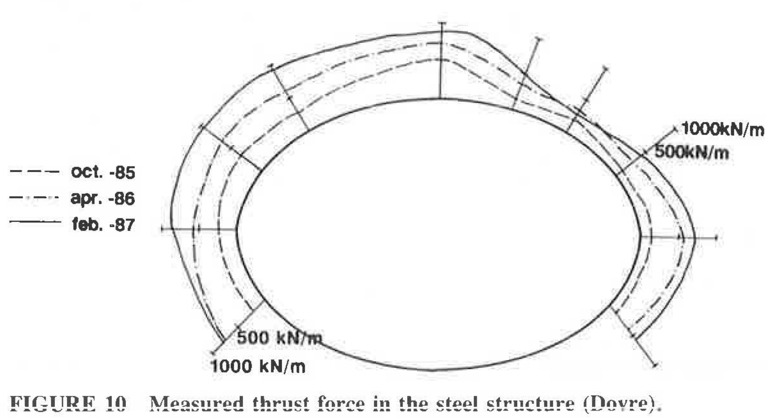


FIGURE 10 Measured thrust force in the steel structure (Dovre).

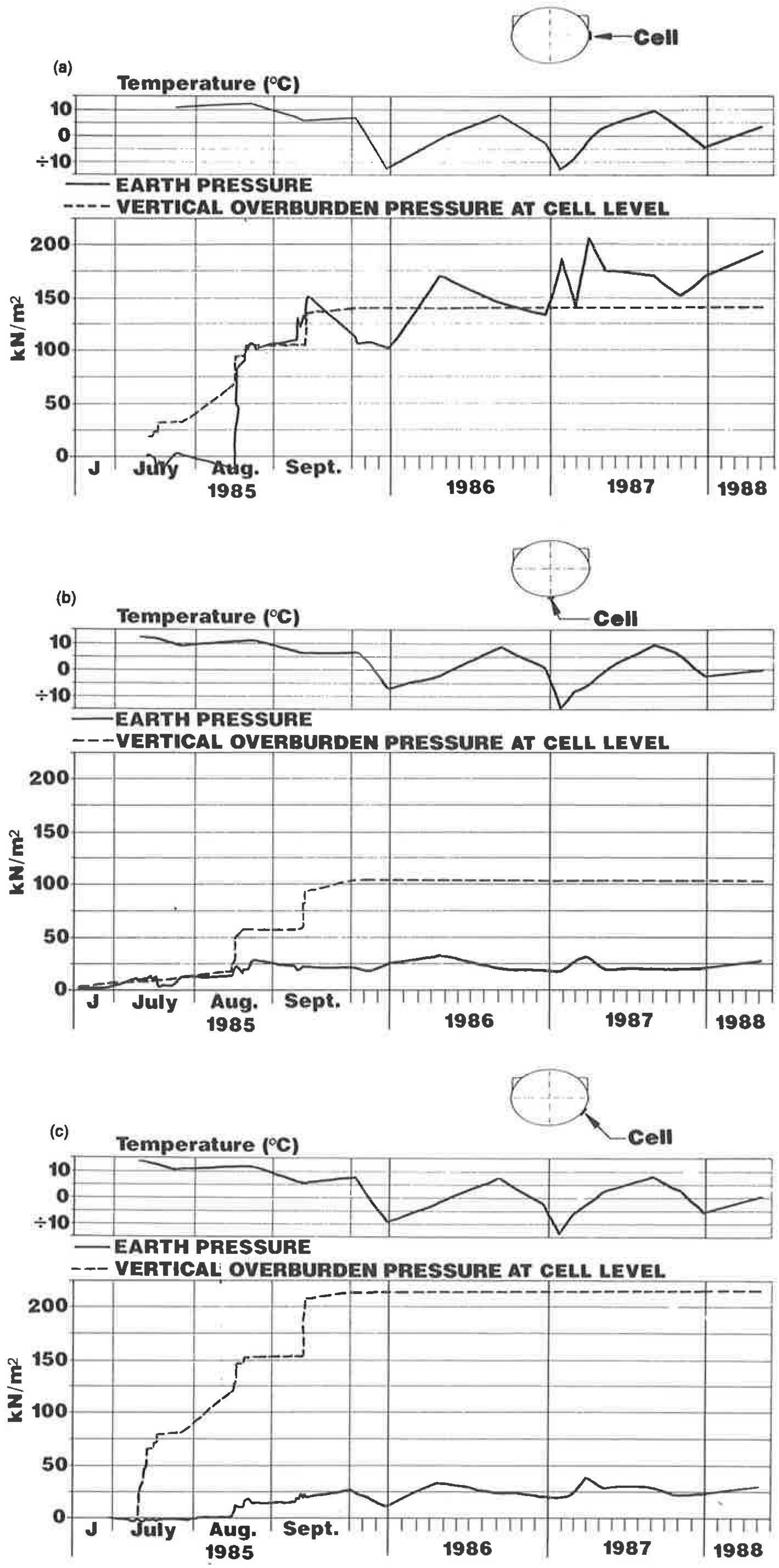
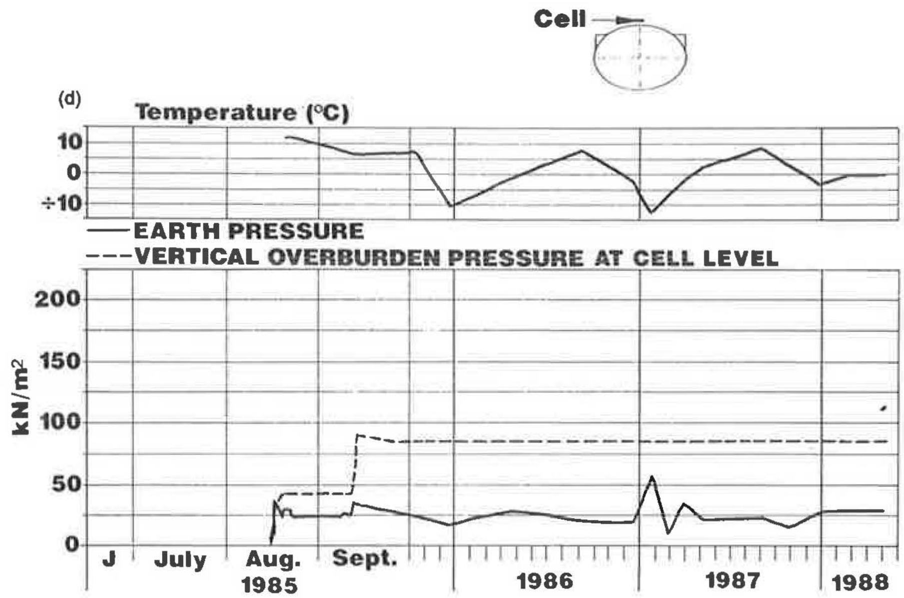


FIGURE 11 Measured earth pressure and temperature (Dovre).

FIGURE 11 *(continued on next page)*



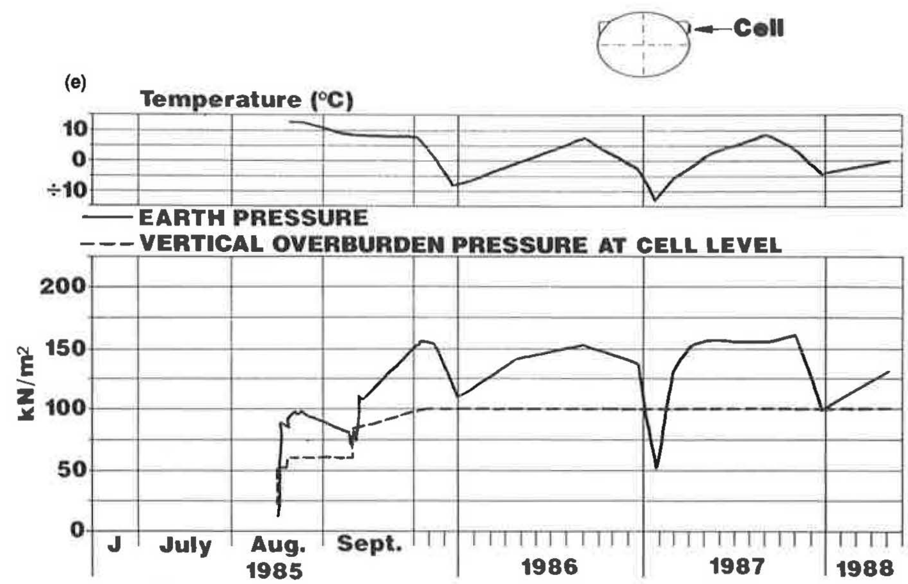


FIGURE 11 *(continued)*

earth pressure at the springline increases considerably during the first 6 months after the end of construction, even reaching values greater than the vertical overburden pressure.

The earth pressure at the haunch area is much lower than at the springline. Earth pressure distribution from the ring-compression theory predicts greatest earth pressure at the haunch.

In the cold climate, the earth pressure around the pipe arch changes with the temperature over the year. The earth pressure distribution around the horizontal ellipse also shows some variations over the year. At the springline, the horizontal earth pressure has increased up to 1.3 times the vertical overburden pressure.

On the lower part of the structure, the earth pressure is relatively small and varies little with temperature over the year.

In the horizontal ellipse, the measured circumferential thrust force in the steel has increased considerably after construction. After 6 months, the maximum thrust force increased 50 percent, and the maximum observed thrust is today almost twice the value measured at the end of construction.

The moment distribution also varies with time, but not as much as the thrust.

Positive arching is measured over the center of the crown. The arching effect is nearly constant, and is 30 percent of the vertical earth pressure over the observation period of almost 3 years, although the measured thrust in the steel indicates negative arching for the structure as a whole.

The long-term deflection and stresses in large-span flexible steel culverts can be controlled by using high quality backfilling material and following established construction procedures.

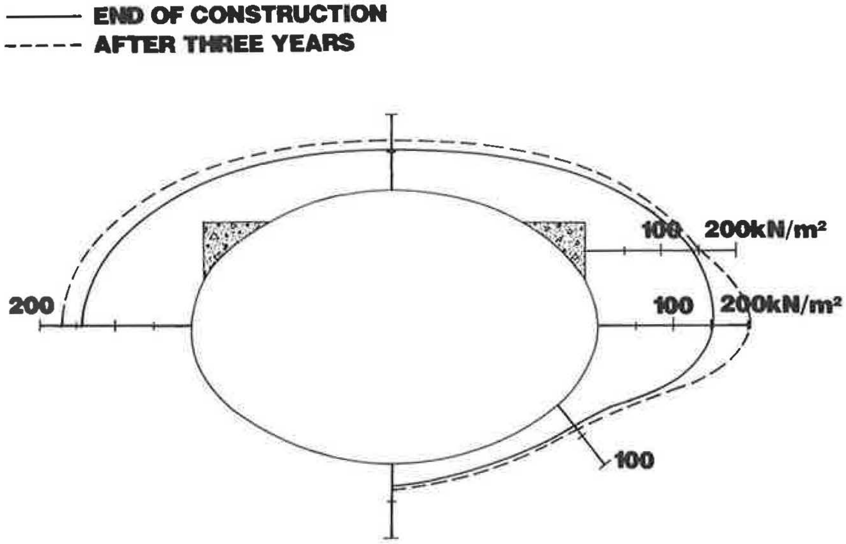


FIGURE 12 Measured earth pressure around the structure (Dovre).

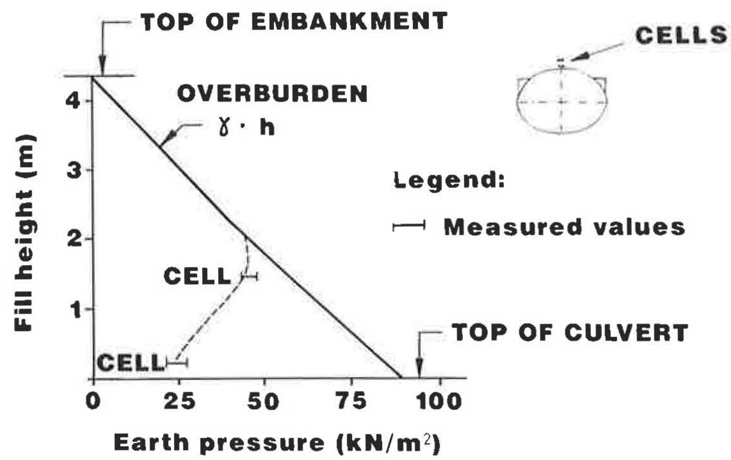


FIGURE 13 Measured earth pressure above the structure (Dovre).

ACKNOWLEDGMENTS

The author wishes to thank Tor Erik Frydenlund and Asmund Knutson for valuable comments during the preparation of the paper and Tor Helge Johansen for his valuable work on the instrumentation and field operations.

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Publication of this paper sponsored by Committee on Subsurface Soil-Structure Interaction.