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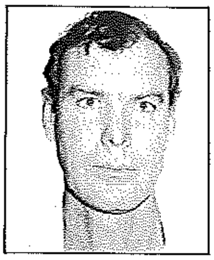
The design, construction and monitoring of Reinforced Earth culverts on an alluvial floodplain

Synopsis

In 1989 four Reinforced Earth culverts were designed beneath a road embankment located on an alluvial floodplain comprising soft clays and silts. The precast concrete clad sidewalls support deck slabs that in turn carry the road embankment above them. Large settlements were predicted during and particularly after construction. This case history reviews the design, construction and monitoring of the structures. Despite the very much greater than predicted settlements, the structures are performing satisfactorily and have resulted in a cost-effective solution.

Samevatting

Gedurende 1989 is vier Gewapende Grond-kasduikers onder 'n padopvulling op 'n alluviale vloedvlak, wat uit sagte klei en slik bestaan het, ontwerp. Die voorafgegote betonbedekte symure stut die dekblaaie, wat dan die opvulling dra. Groot versakkings gedurende en veral na konstruksie is voorspel. Hierdie gevallestudie kyk na die ontwerp, bou en monitering van die strukture. Alhoewel die versakkings veel groter was as dié wat voorspel was, funksioneer die kasduikers bevredigend en het hulle tot 'n koste-effektiewe oplossing gelei.



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Terence Bergmann *received a BSc degree in civil engineering from Natal University in 1972. For the next six years he worked in the construction, design and planning branches of the Department of Water Affairs, being involved mainly with the construction and design of earth dams. In 1978 he joined Candac Construction Company and after a short spell with them and with Robert Leslie and Partners, he joined the Cape Town office of Hawkins Hawkins and Osborn, where he is now an associate. His main involvement in this firm has been in the field of geotechnical engineering.*

Introduction

During the past 15 years the Transkei Government's Department of Works and Energy has carried out a phased reconstruction of the road between Umtata and Port St Johns. The final 22 km section between Tombo and Port St Johns was completed early in 1992. The topography of the coastal strip in the vicinity of Port St Johns is very rugged. This combined with the very varied and often adverse geological conditions found in the area presented numerous design and construction challenges.

Just before the road meets the Mzimvubu River it crosses the floodplain of a relatively minor river, the Ndwalane. Flooding of the Mzimvubu River causes water to back up into the Ndwalane River valley, submerging its floodplain. The most recent major flood event here was in 1987 when the old road, located on this floodplain, was submerged by some 4 m. Similar flood events were recorded in 1974 and 1959.

To limit overtopping of the new road to approximately once in 10 years, it was necessary to raise the new road to an average level of some 5 m above the floodplain by means of a rockfill embankment.

The problem and the solution

Geotechnical investigations had shown that the alluvial floodplain was composed of very soft silts and clays with depths in excess of 20 m. Total settlement of up to 1,9 m was predicted for the embankment. Four major culverts were required to be constructed through the embankment. These culverts were necessary to accommodate a large loss of waterway area owing to the settlement and also to be able to absorb large differential settlements.

Corrugated steel and cellular box culverts were considered. There were, however, problems associated with these types of culvert. Firstly, it was known that the level of confidence as regards the settlement predictions, particularly the rate of settlement, was low. Thus, it was difficult to decide on what settlement criteria to use in the design. The ideal system would not have a limit on movement. Secondly, and also related to the difficulty in determining an upper limit to the settlement, was the fact that any increase in height of the culvert to accommodate loss of waterway area resulted in a considerable change in the proportions of the culvert cross-section, with substantial cost increases; thus one could not afford to be too conservative.

Since it was planned to use the Reinforced Earth technique for several retaining walls on the project, the concept of using the same material for the culverts was developed. The advantages were as follows:

- Economies of scale could be realized.
- The culverts would be able to accommodate large differential settlements without undergoing any structural damage.
- The height of the walls could be increased to allow for a conservative estimate of the loss of waterway area without the cost of the structure being significantly affected.

Site conditions and settlement predictions

The Ndwalane River floodplain was formed by the infilling of an old incised valley during previous sea level changes. The presence of soft silts and clays was therefore to be expected.

Four boreholes were drilled between km 84,2 and km 85,3. The upper 3,0 m to 4,0 m of the typical soil profile comprises a slightly moist to moist, greyish to orange brown, firm silty clay with shale fragments.

Underlying this 'crust', to depths from 12 m to in excess of 20 m below ground level, is a very moist, dark grey, soft to very soft layer of organic silty clay with scattered shale pebbles. The water table at the time of the investigation was between 3 m and 4 m below ground level.

Undisturbed piston samples, 100 mm in diameter, were extracted from depths of 4,0 m and 6,0 m in a borehole at km 84,68 and from depths of 4,0 m, 6,0 m and 8,0 m in a borehole at km 85,24.

Consolidometer tests were carried out on these undisturbed samples. Settlements under the midpoint of each culvert were estimated and are shown in the accompanying table. Compressibility coefficients varied from 0,00049 m^2/kN to 0,00081 m^2/kN.

Consolidation coefficients ranging from 0,084 m^2/year to 1,175 m^2/year were obtained from the consolidation tests. Using the higher of these

Estimated settlements at culvert sites

km	*Total settlement (mm)*	*Settlement after 25 yrs (mm)*
84,280	350	210
84,870	680	410
85,160	1 540	920
85,288	1 940	1 160

values it was predicted that about 60 per cent of the total predicted settlement would take place over a 25 year road life. This meant that the culverts would have to be designed to accommodate settlements well in excess of 1 m.

In order to eliminate the problems associated with settlements of this magnitude, the possibility of increasing the rate of settlement of the embankment across the floodplain with vertical drains was investigated. However, the 1986 cost of R800 000 for doing this was considered prohibitive and it was decided rather to design for these high predicted settlements.

Design of the culverts

General description

The culvert sidewalls were constructed using standard precast concrete elements 140 mm thick, with ribbed 60 mm by 5 mm galvanized mild steel reinforcing strips. Backfill was blasted tillite with a maximum size of 250 mm, and since less than five per cent passed the 75 micron sieve, it was classed as free draining. The height of these walls ranges from 3,5 m to 7,25 m with 4,5 m to 0,75 m of fill on top of the deck slabs.

The deck slabs rest on distribution beams that are 2 m wide and 600 mm deep and are placed 100 mm behind the facing panels. The distribution beams are set on three 150 mm thick layers of crusher run. The clear span across the culvert side walls is 2 m on two of the culverts and 4 m on the other two. The embedment, before settlement, of the Reinforced Earth mass beneath Reno Mattresses placed on the culvert floor was approximately 1 m. The length of the reinforcing strips and consequently the width of the structures is 8 m in all cases, but reduces to 6 m for the wingwalls. A photograph of a nearly completed structure is given in Fig 1 and a typical section is shown in Fig 2.

Overall stability

The stability of the culverts was checked for shear failure of the soft silty clay foundations. It was assumed that a circular failure surface could pass through the road embankment behind the reinforcing strips, through the foundation material on which the structure was founded and out in front of the wall itself. Fig 2 shows a typical cross-section with possible circular failure surface.

For the end of construction case, using an undrained cohesion of 30 kN/m^2 and a friction angle equal to zero, a minimum factor of safety of 1,15 was obtained. This assumed that a condition existed whereby the water table

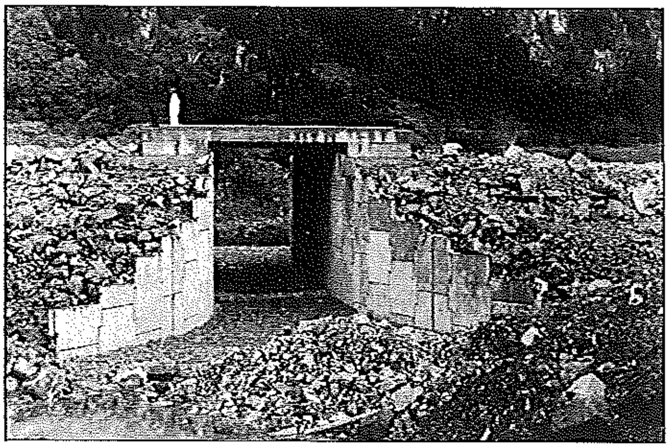

Fig 1: Photograph taken prior to placement of fill over the deck slabs

was just at the surface of the ground, and that saturation of the upper 3 m to 4 m 'crust' had occurred.

In order to increase this short-term stability condition, crushed tillite was used to provide a 2 m deep rockfill blanket that extended across the width of the cross-section. This resulted in an improvement in the short-term factor of safety to 1,30, which was considered to be acceptable.

The long-term stability analysis, using a cohesion of 5 kN/m^2 and a friction angle of 23° (obtained by triaxial tests) gave a factor of safety of 1,47.

Design for settlement

The structures have been designed for a total settlement of 1,5 m. The clearance above the high flood level in the culverts was therefore increased by this amount. Due allowance has been made for the possibility of the road being 'topped up' to original design levels after settlements have occurred. In effect this means that the structures need to be designed for the case prior to settlement where the frictional capacity of the upper reinforcing strips may control and for the case of an additional 1,5 m of fill surcharge on top of the deck slab where the strength of the strips may control.

The culverts rest on a uniformly poor foundation and settlement across the width of the structure was assumed to be directly proportional to the height of the embankment. If 1 500 mm settlement is expected at the shoulder breakpoint of a 7,5 m high fill and zero settlement is assumed at the toe of the fill, then differential settlements of the order of 10 per cent are possible. In practice a certain amount of settlement would take place at the toe of the fill, so this assumption is conservative. Since the standard precast concrete cladding elements can accommodate a differential settlement of only 1,5 per cent, special vertical sliding joints were introduced into the cladding at 3 m intervals (Fig 3).

The length of the reinforcing strips is initially determined as a direct function of the bearing pressure beneath the structure. In this case, however, the strip length had to be lengthened to 8 m in order to satisfy

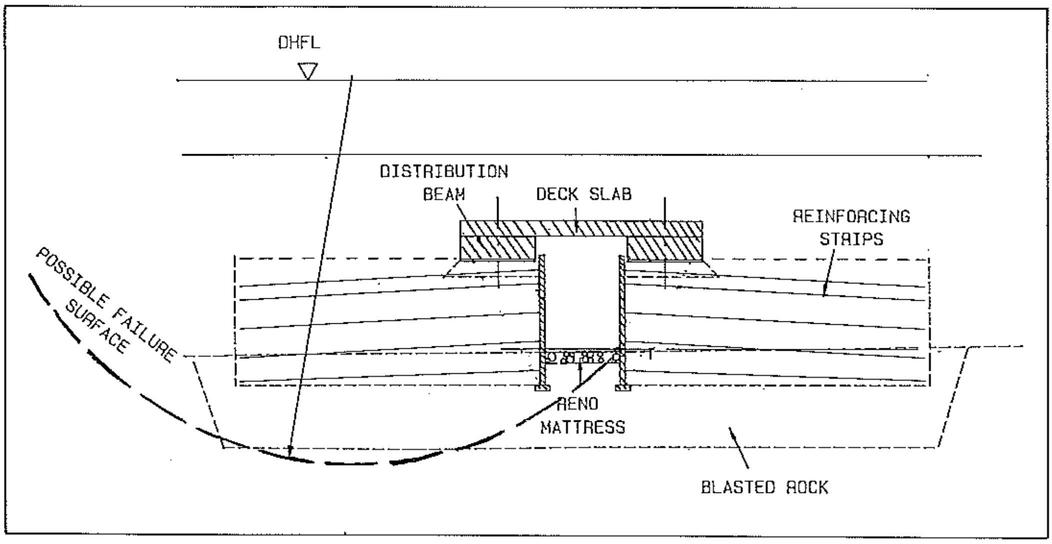

Fig 2: Typical section through a culvert

external stability requirements.

It was assumed that the structures would settle vertically with the embankments and that there would be no tilting of the cladding. This has, in fact, been the case.

Durability

The structures are designed for a service life of 100 years. The lower part of one of the culverts will be almost continuously submerged in water over this period, while the upper part of all of the structures will be submerged only during flooding. It was assumed that the water would be fresh water, but it could be saline at periods of full spring tide. The structures are founded at 1,4 m, 3,1 m, 3,1 m and 7,1 m above mean sea level.

The durability of the structures is dependent on the durability of the reinforcing strips. The structures were designed according to guidelines for walls immersed in fresh water. It was not considered that occasional immersion of the lowermost strips in sea water would have a significant effect on the durability of the strips.

Influence of the water

The high water level of the flood for the extreme event is up to 2 m above the level of the road. As the flood waters rise and fall, so they will first saturate and then drain from the backfill. The rate of saturation and draining depends on the permeability of the Reinforced Earth backfill. A lag between the water level inside the backfill and outside the cladding of the structures introduces hydrostatic forces. These additional forces are carried by the reinforcing strips.

Saturation of the backfill could also reduce its frictional properties, increasing the coefficient of horizontal earth pressure and consequently the forces on the strips still further. Resistance to pull out of the strips will, at the same time, be reduced by the combined effect of the buoyancy of the fill beneath the water level and the reduction in apparent coefficient of friction between the strips and the fill. A considerable increase in the density of reinforcing strips would be required to combat these effects. Using free draining backfill minimizes these effects and the need to increase the density of the reinforcing strips was thus avoided.

Construction of the culverts

Excavations for the rockfill blankets were about 500 mm deeper than the water table, but as it was during the dry season, the ground surface was stable enough for this work to be carried out by means of a Liebher 952 excavator without undue problems. The geotextile beneath the rockfill, and the rockfill itself, then had to be placed in water, but again access was possible from the sides of the excavations and end tipping posed no problems.

The concrete panels for the cladding were precast and ready by the time the rockfill was in place. After trimming of the batter slopes had been completed, there were sufficient interlocked rocks on the surface of the slope for the designed Reno Mattress protection above the wingwalls to be omitted. However, the floors were finished with a 500 mm deep Reno Mattress as designed.

Care had to be taken to prevent the coarse blasted tillite from damaging the galvanized reinforcing strips. The material was end tipped into fill and bulldozed into position. Compaction was according to standard rockfill method specification.

The rest of the embankment was constructed ahead of the culverts. A requirement in the specifications was that the fill across the floodplain be constructed early on in the contract period to ensure that as much settlement as possible took place before construction of the layer works. If this had not been the case, it would have been possible to build the road embankment and culverts at the same time.

Monitoring of the culverts

Construction of the embankment across the Ndwalane floodplain began early in 1989. It was brought up to its full height in two stages early on in the contract in order to allow as much settlement as possible to take place during the contract period. Construction of the culverts began about a year after the embankment had been completed. Monitoring of the culverts began in March/April 1990. Construction of the culverts was completed approximately one year later. Monitoring points consisted of 'Hilti' nails, which were shot into the panels. Each wall of each of the culverts had a monitoring point at the inlet and outlet and at the midpoint within the culvert. Monitoring generally involved levelling at monthly intervals, for the duration of the contract. Since completion of the contract early in 1992, monitoring has been carried out at approximately three-monthly intervals.

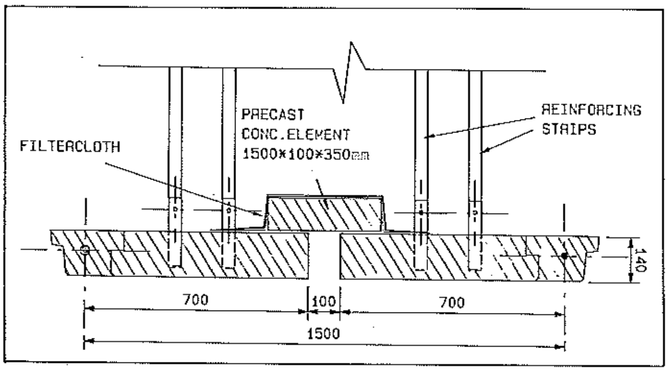

Fig 3: The sliding joints

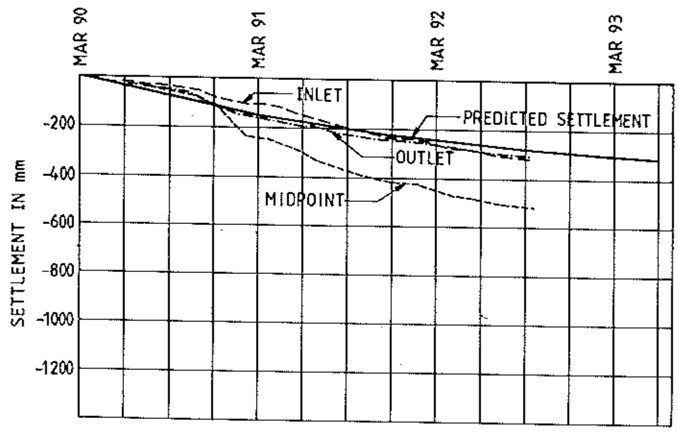

FIG. 4.1 CULVERT AT km 85,160

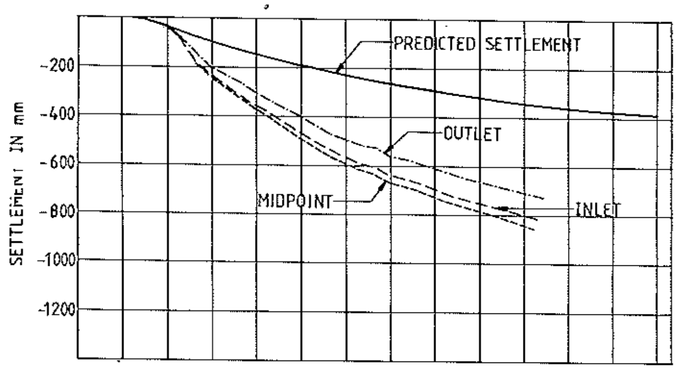

FIG.4.2 CULVERT AT km 85,288

Fig 4: Time settlement plots for inlet, outlet and midpoint

Figs 4.1 and 4.2 are time settlement plots for the inlet, outlet and midpoint of the culverts at km 85,160 and km 85,288. Superimposed onto these is the predicted settlement curve at each culvert position. Settlements recorded to date for the other two culverts are not as great as for these and the information is not presented.

In both cases the measured settlements are significantly higher than the predicted settlements. This is probably due largely to inaccuracies in estimating the rate of settlement and particularly the assumption of drainage path length.

The culvert at km 85,288 has settled the most, with 820 mm of settlement being recorded at its midpoint to date. The maximum differential settlement recorded is 220 mm, between the midpoint and outlet of the culvert at km 85,160. Over a distance of 14 m, this represents a differential settlement of 1,6 per cent. This figure is expected to increase as more settlement takes place.

Unfortunately no measurements were made at the toe of the wingwalls, but it is expected that the differential movement along the wingwalls could be higher than that measured for the central portion of the culvert.

Thus while the maximum total settlement which has taken place to date is more than double the predicted value, differential settlement is still well below the design allowance of 10 per cent.

At this stage there is very little, if any, noticeable deformation in the walls of this culvert. The edges of the vertical movement joints are still approximately parallel and it would seem that most of the differential movement has been taken up in small relative movements of each individual panel.

This illustrates the point made earlier, that the use of the Reinforced Earth technique allowed the use of conservative design criteria without adding substantially to the cost of the structure. The introduction of movement joints every 3 m, while adding little to the cost, increased the differential settlement that could be accommodated from 1,5 per cent to 10 per cent.

Photographs showing the culvert at km 85,288 and the effect of the settlement to date are shown in Figs 5 and 6.

Cost analysis

The total cost of the four culverts amounted to R804 128, inclusive of escalation.

The equivalent cost for possible alternatives would have been R982 000 for multi-arch metal pipes and R1 132 000 for reinforced concrete box culverts.

It is interesting to note that the actual cost of the four culverts is approximately equal to the 1986 estimated cost of accelerating the settlement of the embankment using vertical drains. Bearing in mind that had this alternative been accepted, the culverts would still have been required, then the concept of designing for the settlement has been a cost-efficient solution.

Conclusion

This case history describes a cost-effective technique for culvert construction on soft foundations. The use of Reinforced Earth has resulted in culverts that can absorb large differential settlements without structural deformation. The culverts are performing satisfactorily and in this case have resulted in a considerable cost saving over more traditional construction methods.

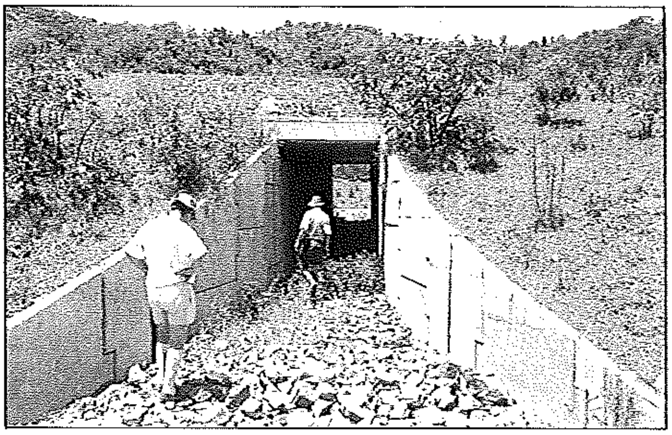

Fig 5: Completed structure at km 85,288 after two years' settlement (820 mm at midpoint)

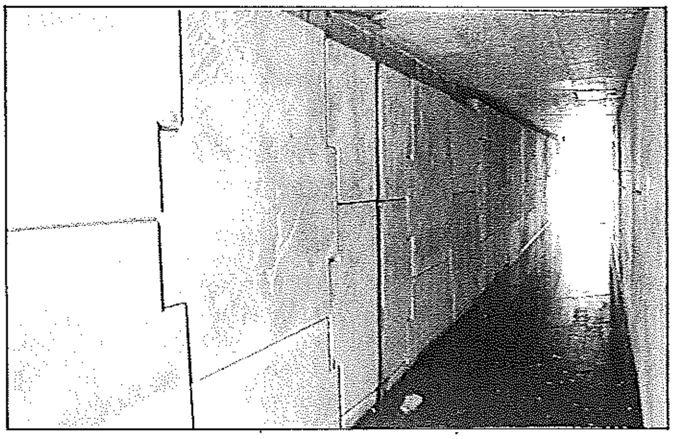

Fig 6: Closer view of Fig 5 showing the deck soffit and the cladding panels after two years of settlement - no signs of distress are visible

Discussion on papers

Written discussion on the technical papers in this issue of the *Journal* will be accepted until 30 April 1994. This, together with the authors' replies, will be published in the Third Quarter 1994 (September) issue of the *Journal*, or the issue thereafter. For the convenience of overseas contributors only, the closing date for discussion will be extended to 31 May 1994. Discussion must be sent to the Directorate of SAICE.

Such written discussion must be submitted in duplicate, should be in the first person present tense and should be typed in double spacing. It should be as short as possible and should not normally exceed 600 words in length. It should also conform to the requirements laid down in the 'Notes on the preparation of papers' as published on the inside back cover of this issue of the *Journal*.

Whenever reference is made to the above papers this publication should be referred to as the *Journal of the South African Institution of Civil Engineers* and the volume and date given thus: **J SA Inst Civ Eng, Vol 36, No 1, First Quarter 1994.**