Analysis of the failure of the Minte Creek culvert

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Abstract A persistent rainfall that lasted more than 30 h on 6–7 May 1995, caused the sudden failure of an embankment on highway 225, in southern Chile. Under this embankment a culvert existed, through which the water of Minte Creek was evacuated. The failure left an open pit, some 20m wide by 18m deep, cutting across the road. Seven vehicles fell into the ditch, and 27 persons died as a consequence. This paper presents the analysis of the process of failure. The conclusion is that culvert entrance was submerged some 6 to 8 m for more than 15 h. This caused seepage through the lower layers and a piping phenomenon of the embankment material, producing its collapse. From the analysis of this catastrophic failure it appears convenient that assessments of the possible consequences of a failure be considered a requirement for engineering decisions in the design process.

INTRODUCTION

Highway 225 in southern Chile (see map in Fig 1) is a two-way traffic paved road, which connects the city of Puerto Varas with the village of La Ensenada, along the southern shore of Lake Llanquihue. This is a scenic road, along which many weekend cottages and holiday houses have been built. On the weekend of 6–7 May 1995 a persistent and continuous rainfall, lasting more than 30 h, caused the sudden failure of an embankment of the road, 7 km out of Puerto Varas. Under this embankment a culvert existed, through which the water of Minte Creek crossed, on its way to the outlet in Lake Llanquihue. The failure occurred at approximately 2000 h. on Sunday 7 May, when many vehicles were returning back to the cities of Puerto Varas and Puerto Montt, after the people had spent the weekend in the countryside. In the area, rain was still falling, it was well after sundown and there is no artificial lighting.

The failure left an open pit, approximately 20 m wide by 18 m deep, that cut across the road completely, and through which the flood discharges of the Minte Creek were evacuated. Seven vehicles fell into this created open pit before the traffic was stopped. As a consequence, 27 persons died.

The ensuing investigation of the failure required a technical report from the Universidad de Chile. In what follows, the analysis of the principal factors that explain the failure are presented, together with a discussion that may contribute to the improvement of engineering design decisions.

BASIC FACTS

Climate in the study area is temperate and rainy during the whole year. Mean air temperatures vary between 7°C in the winter (July) and 15.5°C in the summer (January). Annual mean precipitation is around 1800 mm. The origin of precipita-

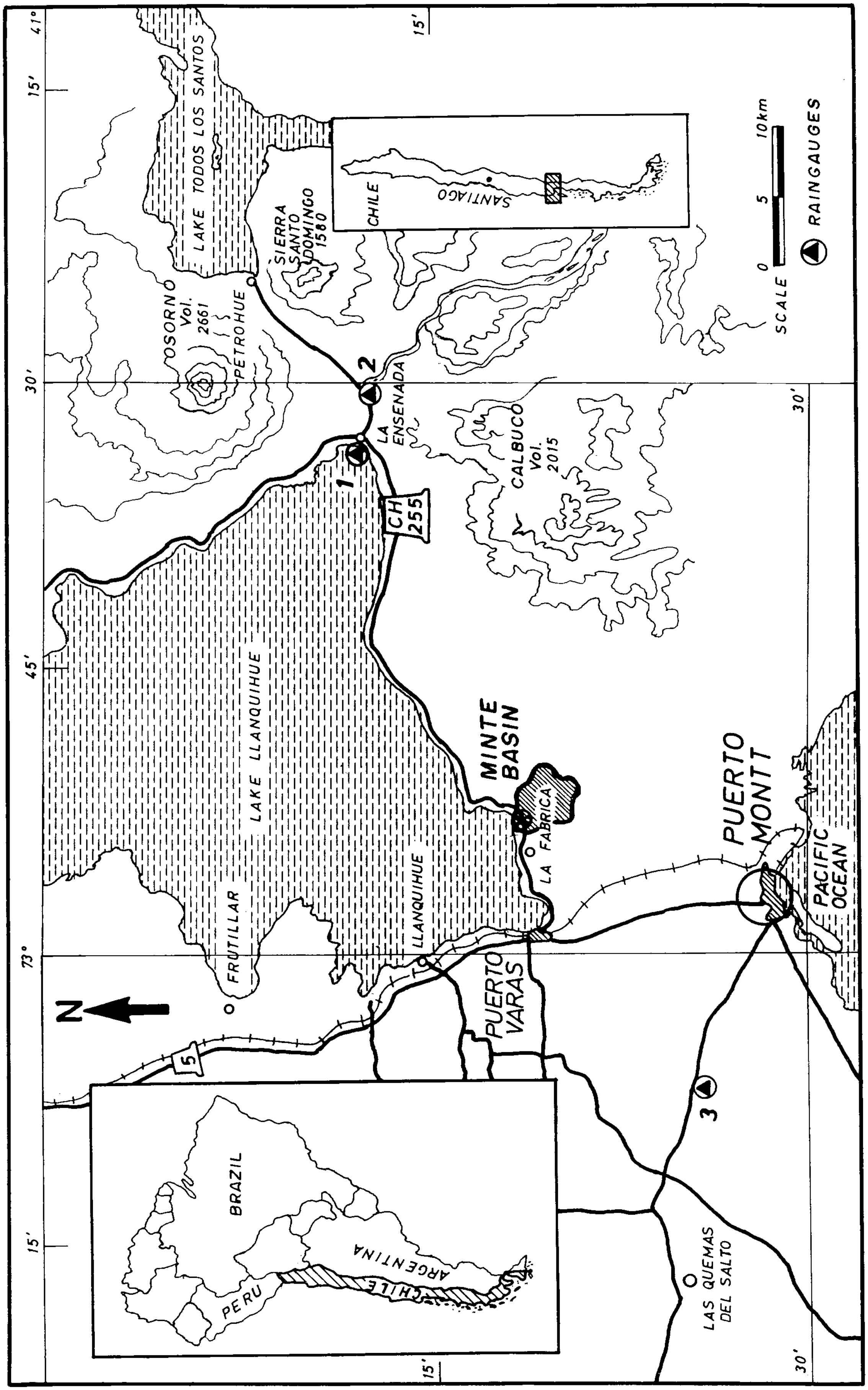

Fig. 1 Minte Creek basin: map of the area.

tions is the movement of fronts coming inland from the Pacific Ocean in a southwest to northeast direction. Rainfall presents a seasonal effect with relatively lower monthly values in the period from November to March.

The Minte stream basin has an area of 14.62 km^2, at the failed culvert cross section. The landscape is marked by low hills, separated by portions of swampy lowlands in some areas, that tend to flood during storms, draining slowly. The highest elevation in the basin is 139 m a.m.s.l., and the outlet in Lake Llanquihue is approximately at 60 m a.m.s.l. Soil is composed mainly of mixtures of clays, silts and sands, forming a quite impervious surface. Vegetation corresponds in most parts to pasture lands with patches of native rainforest.

CULVERT CHARACTERISTICS

According to the data provided by the Highway Division of the Ministry of Public Works, the culvert that failed was an adapted work of the original concrete culvert existing prior to 1964 which allowed the road crossing (Route 225) of the Minte Creek. In this reach the creek slope is about 3% and its bed sediment is composed of a well graded mixture of fine material (clay, silt, sand and gravel).

It seems that as part of the highway reconstruction plan undertaken by the Chilean government after the big earthquake of May 1960, the original road was raised making it necessary to heighten and lengthen the supporting earth embankment. The project drawings available for the study showed that the original Minte culvert was 30.3 m long and its cross section was 2 m wide and 1.4 m high. During the raising and upgrading of the highway, the earth embankment on which the

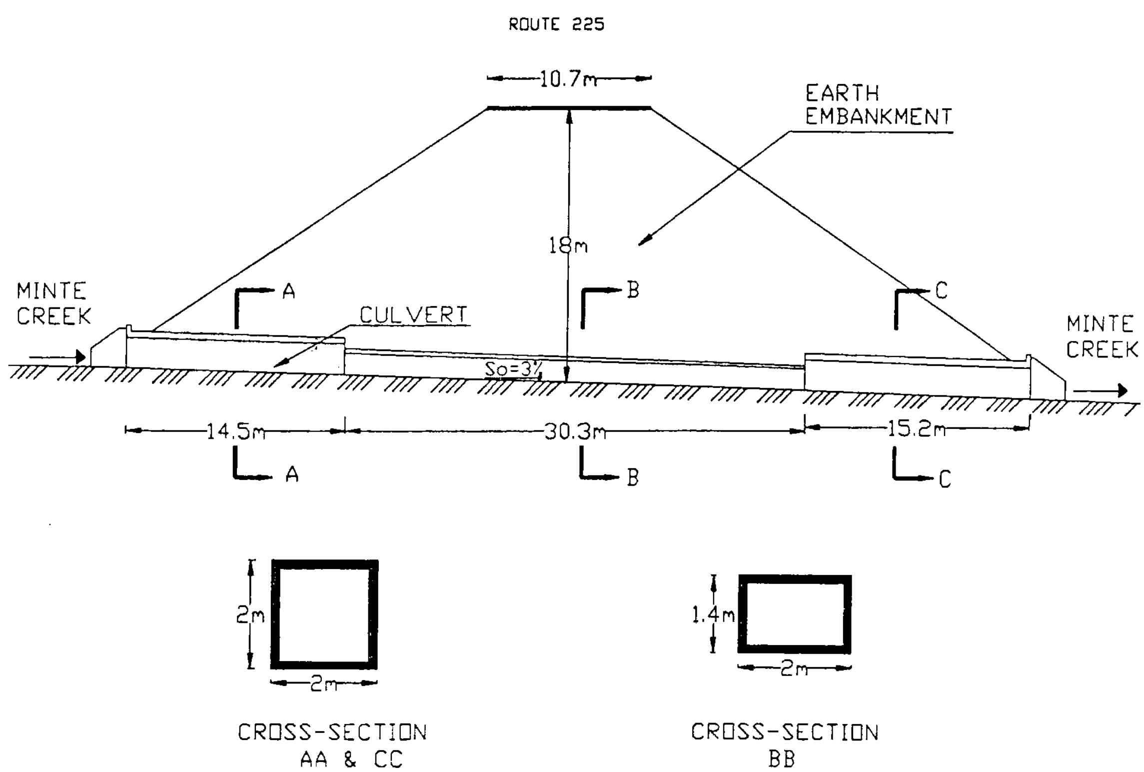

Fig. 2 Culvert and embankment cross section.

pavement was constructed was heightened by about 7 m, and the culvert was enlarged both in length and in cross-section. An upstream piece 15.2 m long as well as a downstream piece of 14.5 m, both having a 2 × 2 m cross section, were added to the original culvert. In this way the new embankment reached a total height of about 18 m and the culvert spanned nearly 60 m, with a cross section area of 4 m^2 that was reduced to 1.8 m^2 in the inner reach. Fig. 2 depicts the main characteristics of the Minte culvert as described above.

ANALYSIS OF RAINFALL RECORDS FOR 6–7 MAY 1995

On the map (Fig.1), the location of three raingauges in the vicinity of the Minte basin is shown. In Table 1, daily observed precipitation for these raingauges for 6–7 May 1995 are included. It is worthwhile to indicate that in the area there had been only two days without rainfall before this storm.

A frequency analysis of the data at raingauge no. 1, indicates that return periods in the order of 27 and 22 years can be associated with the individual daily precipitation observed for 6 and 7 May respectively. The two-day total observed precipitation, however, has a return period well in excess of 100 years.

The only available recorded rainfall, at raingauge no. 3, has been used to plot the hyetograph in Fig. 3. This shows maximum intensities below 10 mm h^{-1} at the watershed, which are certainly quite low. This recorded rainfall, shows also that it stopped raining at 1900 h on 7 May. However, according to eyewitness reports, it was still raining hard at the site, when the failure took place. This fact is in agreement with the normal direction of movement of fronts in the area. The orographic effects and the delay in the occurrence of the rainfall towards the east, is confirmed by the values observed at raingauges no. 1 and no. 2.

Table 1 Daily precipitation (mm).

Day	Raingauge no. 1	Raingauge no. 2	Raingauge no. 3
6 May 1995	78.6	116.0	67.2
7 May 1995	74.9	76.0	40.3
2-day total	153.5	192.0	107.5

SYNTHETIZED RUNOFF FOR THE STORM

The hydrograph generated by the storm, at the culvert, was synthesized using the runoff curve numbers (*CN*) developed by the US Soil Conservation Service, and the triangular unit hydrograph concept (US Department of the Interior, 1977). The rainfall input was the hyetograph in Fig. 3. Soil characteristics and vegetation cover were estimated using aerial photos and field surveys, and slopes were determined using topographic charts. Hydrographs were constructed for a range of *CN* values between 80 and 90 and a range of values for concentration times (*tc*) between 2 and 4 h.

In Fig. 3 some of the synthesized hydrographs are shown. Peak runoff values varied between 22 and 30 m^3 s^{-1}, and would have occurred between 1030 and 1130 h on 7 May 1995. Also the hydrographs show two smaller peaks: one, in the order of

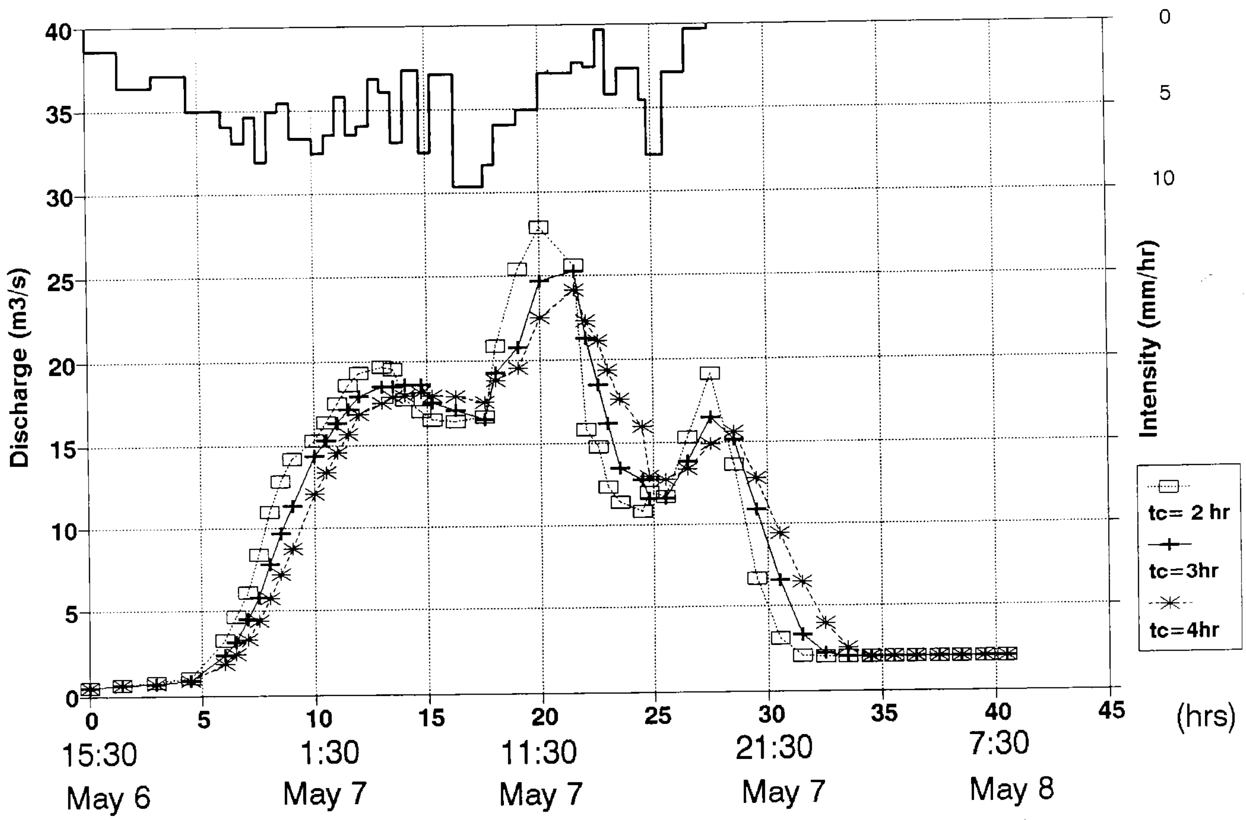

Fig. 3 6–7 May 1995 storm hyetograph and synthesized hydrographs.

15–22 $m^3 s^{-1}$ occurring at around 0400 h and the other in the order of 15–20 $m^3 s^{-1}$ at around 1830 h on the same day.

The resulting maximum discharges were corroborated by approximate estimates, made through hydraulic computations based on eyewitness reports of water levels in a short channelled portion of the stream some 300 m upstream of the failed culvert.

CULVERT AND EMBANKMENT BEHAVIOUR DURING THE STORM

As shown later, at least three main factors played a decisive role in the embankment sudden failure. First, during several hours the culvert proved to be insufficient to convey the flood discharges, causing its entrance to be submerged, thus causing the embankment to act as a small pervious dam. Secondly, as a consequence of this and because of the hydrograph shape, the upstream water levels successively rose and decreased resulting in a three-cycle embankment saturation-drainage process that lasted for more than 15 h. Thirdly, the internal discontinuities in the culvert cross section resulted in a couple of critical seepage points which caused internal piping, probably enhanced by the shortening of the seepage path due to the upstream and downstream embankment toe failure.

The above conclusions were drawn from the analyses performed on the culvert hydraulic behaviour (which was focused on the determination of its hydraulic capacity and flow conditions) as well as on the embankment seepage flow and pore pressure and gradients, based on the determination of a flow net within the saturated zone of the embankment.

With reference to the hydraulic behaviour of the culvert, due to the natural conditions existing in the basin and creek (some eroded soil and dried vegetation due to agricultural activities, small scale logging, debris carried by the sheet flow, etc.) and the information provided by local people and authorities in the sense that the failure could have been caused by a debris blockage at the culvert entrance, it was first necessary to determine the maximum open channel flow discharge characteristic of the concrete conduit. To this effect, two computer simulations were run assuming a friction factor (*f*) with extreme values of 0.025 and 0.050. The results obtained showed that the limiting discharge was in the range from 10.9 to 12.7 $m^3 s^{-1}$. As on the other hand the flood hydrograph showed that discharges greater than 12 $m^3 s^{-1}$ persisted for 15 h or more, it readily became clear that the most critical stage of the failure was associated with a pressure flow and build up of an hydraulic head at the culvert entrance. This latter phenomenon was mainly due to the insufficient capacity of the culvert rather than to blockage effects.

The above conclusion is arrived at after examining the graph of Fig. 4, which is a plot of the water stage (Z) measured from the top of the culvert entrance as a function of time, calculated with f = 0.050. Here, $t = 0$ corresponds to the starting time of the flood (1530 h, 6 May 1995) and water stage $Z = 0$ denotes the condition for which the flow begins to behave as a close conduit flow. It is seen that the hydraulic head at the culvert entrance started building up at approximately $t = 9$ h (0030 h, 7 May 1995). From then on, the pressure rose to a maximum, reaching about $Z = 4$ m at $t = 12$ h (0300 h). It was followed first by a water level reduction, and then by a steeper and higher rise which led to a second maximum around $Z = 9$ m at $t = 20$ h (1130 h). Then the water stages decreased again to a minimum, rising thereafter to a third and last peak of $Z = 3$ m at $t = 27$ h (1830 h). An hour or

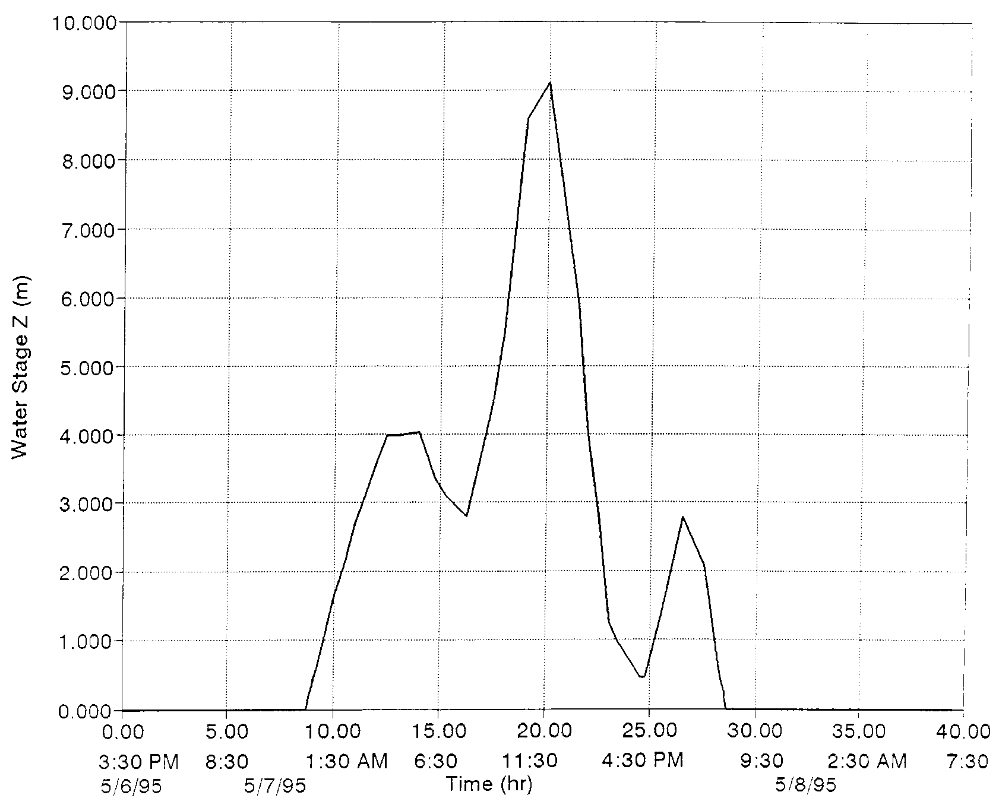

Fig. 4 Water stage at the entrance of the culvert.

so later, the sudden collapse of the embankment occurred. This sudden failure is evident from the catastrophic consequences it had. The unexpected opening of a deep pit and the rather low visibility conditions (at night and still raining) precluded any reaction from the car drivers who at this time were about to transit along the embankment.

From what has been described above, the rising and lowering of the water level played a fundamental role in the road collapse, because it exposed the earth embankment to a process of successive saturation and drainage. In fact, during the rising stages a seepage flow was established in the downstream direction, but as the upstream water level decreased, new pressure gradients forced the flow in the opposite direction. The flow net drawn for the most severe condition (maximum upstream water stage) revealed that the downstream seepage flow resulted in high pore pressure gradients at the downstream face of the embankment, particularly at its

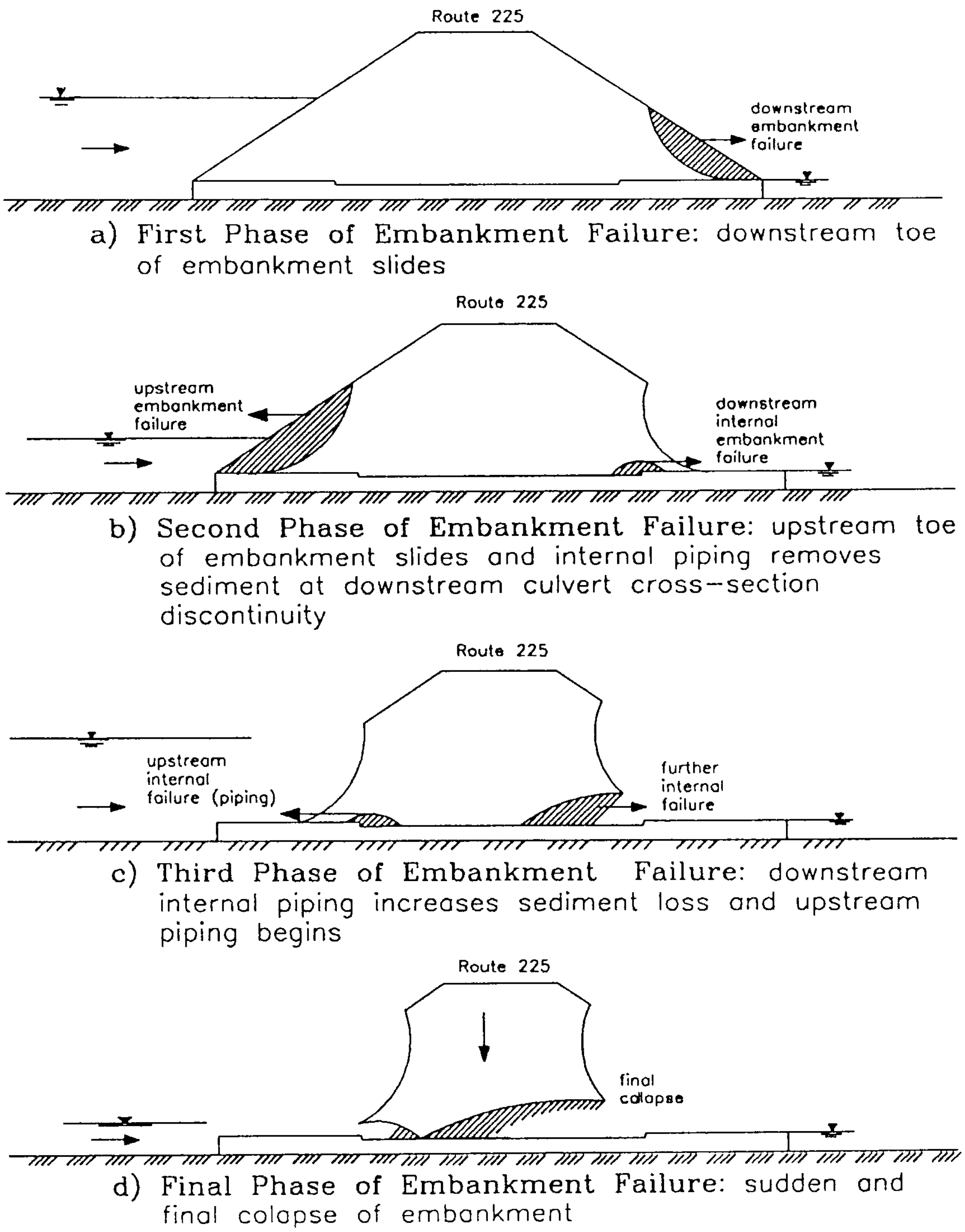

Fig. 5 Phases of embankment failure.

toe and surrounding lower zone where the seepage flow emerged. These gradients exceeded the critical values, thus resulting in piping and failure by sliding of the lower part of the embankment face.

At the same time, due to high internal pore pressure gradients at the culvert cross section discontinuities (similar to those of the embankment face), it is highly probable that a piping phenomenon also occurred around the interface between the culvert and the embankment, causing the loss of sediment. Furthermore, this may have been enhanced by the shortening of the seepage path once the downstream face failed as the upstream water stage increased.

A similar situation occurred later in the upstream face when the seepage flow reverted its direction as the upstream water stage decreased. In Fig. 5, a graphical representation of the four main phases of the embankment failure, as envisaged from the above analysis, is depicted.

FINAL DISCUSSION AND CONCLUSIONS

It is clear that in this case, the effect caused by a moderately high, but very long and persistent rainfall, was the initial factor that triggered the sequence of events that caused the final collapse of the embankment. Normally, this is not a situation which is explicitly considered as a design condition. In fact, flood discharge estimates, for the design of highways and roads are normally made considering peak flows from short and intense rainfalls. The accepted risk in the design, is a function of the return periods, of anything between 25 and 100 years, associated with these peak flows.

Admitting that the catastrophic consequences of the reported failure were due to a very adverse combination of circumstances, it is evident that an embankment 18 m high on a road is potentially much more dangerous than one of a more moderate height, all other conditions being alike.

It is apparent then, that to establish engineering design criteria, however unimportant one might deem a certain civil work to be, it is a requirement to appropriately assess the possible consequences that a failure of that work could have. This is particularly important if human lives might be jeopardized.

REFERENCE

US Department of the Interior. Bureau of Reclamation (1977) *Design of Small Dams*, second edn, revised reprint.