ENGINEERING ASPECTS OF THE JULY 8, 1971 EARTHQUAKE IN CENTRAL CHILE

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SYNOPSIS.

This paper presents a review of the effects of the earthquake on several structures like hospitals, schools and dwellings showing the comparative behaviour of different materials. Damages to harbour facilities, bridges, earth dams, tailing dams, railroads and water supply systems are discussed. Design practice is commented.

INTRODUCTION.

At 23.09 local time, on July 8, 1971, an earthquake of magnitud 7.5 (Berkeley) stroke Chile between parallels 28 and 36 S., Fig. 1. The hypocenter was located in the ocean, latitude 32°45' S. and longitude 71°58'W. with a depth of 60 Km. (Ref. 1). This area is seismically very active. Another earthquake in 1965 had the epicenter located approximately at the same place with about the same magnitude and focal depth. According to instrumental data, the mechanism could be a normal reverse fault of compressional type (Ref. 2).

Five accelerometers were installed in the affected area but only one of them, located in the basement of the Physics Building of the Faculty of Physical Sciences and Mathematics of the University of Chile worked properly. This building is founded on approximately 80 m. of dense gravel with shear wave propagation velocities of 470 m/sec. from 0 to 9 m. deep; 840 m/sec from 9 to 46 m. deep, and 1200 m/sec, from 46 to 80 m. deep. Below this rock is found.

The maximum recorded acceleration was 0.17 g., 140 Km. far from the epicentral area. The record length was about one minute. These characteristics are similar to those of the 1965 earthquake.

Casualties were 85 deaths and 447 seriourly injured persons. Most of these casualties were due to the collapse of adobe or unreinforced brick walls and parapets. Some of these occurred even in intensity VI zones. This can be compared with the 1965 earthquake where 26 deaths ocurred due to the above mentioned causes and 222 due to the failure of a tailing dam.

Losses were estimated in US $ 250 million which includes 35,000 dwellings destroyed or damaged beyond repair; damage to schools, hospitals and other buildings; water, electricity and communication systems; public transportation partially disrupted and some industries temporarily paralized. Some of these effects are described herein.

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SCHOOLS AND HOSPITALS.

Schools and hospitals in the area stricken by the earthquake were built of many different materials and varied very much in age. The types of construction were : adobe, wood, reinforced masonry, reinforced concrete and steel. From preliminary reports after the earthquake, the following statistics was obtained :

Construction type	Number of Schools	Seriously damaged(%)	Number of Hospitals	Seriously Damaged (%)
Adobe	71	72%	8	66%
Wood	62	10%	2	--
Reinforced masonry	41	50%	6	40%
Reinforced concrete	44	10%	9	20%
Steel	91	6%	-	--
Composite	--	--	5	60%

This statistics excludes school located in the Province of Santiago were the intensity was VI and VII MM and refers to 309 schools. The total number of schools in the affected zone is 1301. 575 classrooms had to be reconstructed.

From 8273 beds in 38 hospitals in the zone, a capacity of 1410 beds was lost. 13 of these hospitals had been constructed in the last 20 years and only one had significant damage.

EARTH DAMS

Several earth dams for irrigation existed in the area under study. Some of them suffered serious damage meanwhile others did not suffer altough their distance to the epicentral area was similar.

Catapilco dam is located close to the village of Catapilco, Fig. 1. The storage capacity is approximately 5 million cubic meters. The length of the main embankment is 500 m. and its maximum height is 14 m. Slopes are shown in Fig. 2. The downstream slope has its upper 2 m. with a steeper slope covered with rocks already embedded in the clay. Upstream slope has a rock wall very recently built of 1,2 m. height for protection against wave action. The embankment is homogeneous composed of sandy clays and clayey sands of non uniform compaction. Their natural unit weight is approximately 2.1 ton/m^3. The shear resistance at 97% Proctor density is given by $\phi = 35°$ and a cohesion c =0.8 ton/m^2 (Ref. 3).

With these soil parameters the factor of safety computed in Ref. 3 was :

Upstream slope. Rapid drawdown. Static: FS=1.67;Dynamic:FS=1.07 (0.2g)
Downstream slope. Full capacity.Static: FS=1.21;Dynamic:FS=0.82 (0.2g)

This dam is about 80 years old and during the 1965 earthquake suffered some damage consisting in longitudinal cracks in the top of the embankment and some slides that comprised the upper part of the upstream slope and the upper 4 meters of the downstream slope. During the 1971 earthquake the damages were similar to those in 1965 but now the upstream rock wall was damaged in several places. During both earthquakes the water in the reservoir was 10 m. below the top.

Lliu Lliu dam is located 10 Km. south of Limache, Fig. 1. The characteristics of the dam are the following : Capacity : 2.7 million m^3. Maximum height : 20 m. Width of the top : 6 a 8 m. Length : 500 m. Upstream slope : 1.7:1 (h:v). Downstream slope : 1.5:1. The embankment is homogeneous with soils SC and CL (USCS). Density is approximately between 87 to 95% of maximum Proctor density. (Ref. 4). The factor of safety computed in Ref. 4 is :

Considering c=0. Downstream slope. Full capacity. Static FS = 1.10 Dynamic FS = 0.89 (0.10 g. uniform through the height).

Considering c=1.2 ton/m^2 the dynamic FS = 1.4

In both cases the internal friction angle of the soil $\phi = 35°$.

Damage consisted in longitudinal cracks; some settlement; some local slides observed in the downstream slope and slides in the upstream slope comprising the upper 5 meters. Some cracks were about 100 m. long. Similar damages were observed during the 1965 earthquake but no repairs were made after it.

The water level during the earthquake was 4.6 m. below the top.

Other dams existed in the area. Collagua dam about 10 Km. north of Calera with a capacity of 1 million m^3, was recently finished and did not show any damage. El Melón dam 5 Km. east of Calera, a very old dam recently repaired did not show any damages either. These two dams were lower than Catapilco and Lliu Lliu.

Limáhuida dam, located near Illapel suffered some cracks 2 or 3 cm. wide and 10 m. long. Some initial sliding was observed in both slopes. This dam is homogeneous with about 10 m. maximum height and approximately 1 million m^3 capacity. About 13 other dams of different sizes had damage in the embankments or spillways and valves. Even some dams for overnight storage collapsed in Choapa Valley (Salamanca).

TAILING DAMS.

Many tailing dams existed in this zone and some of them collapsed. Cerro Negro and Illapel tailing dams collapsed and the tailings flowed several kilometers killing only one person the first one. Illapel dam was about 100 x 100 m. with 8 m. high and slopes about 1:1. Three sides failed but most of the tailings flowed through one side that collapsed completely. A Tailing dam in Cabildo of similar characteristics to the Illapel dam, did not fail. Neither failed the dam in El Cobre where a big disaster occurred in 1965 with 222 deaths. Other tailing dams in Petorca were reported with some damage.

WATER SUPPLY SYSTEMS.

The cities of Valparaíso and Viña del Mar with a population of 560.000 inhabitants were seriously affected in their water supply. Three systems provide for the necessary water :the aqueducts from Las Vegas and Concón, at the Aconcagua river, with capacities of 1450 and 750 lit/sec., respectively, and the Peñuelas reservoir, that provides up to 400 lit/sec.

The aqueduct from Las Vegas has a total length of 84 Km. It flows without pressure in a cross section of reinforced concrete shown in Fig. 3 There are also many syphons that are built in the same way with a heavier reinforcement when the pressure does not exceed 40 m.; otherwise they are built in steel. Reinforced concrete pipes have 15 m. in length and 0.5 m. separations that were poured later in order to prevent cracks due to shrinkage of concrete during the curing.

In the 1965 earthquake a total number of 1417 transverse fissures and cracks appeared in the reinforced concrete pipes and joints. Many joints failed by construction negligency : the 0.5 m. separations had been used to retire the forms and the joint reinforcement had been bent out of the position; the joints had been concreted then without a proper rearrangement of bars. Fissures at reinforced concrete pipes were atributed to soil compaction during the earthquake and to the stiffness of these pipes. When flowing without pressure the water leakage was not important, but in the syphons sections water leaked under pressure causing erosion of the bed. The subsequent lack of support developed the fissures into cracks and caused even the destruction of some pipes. The steel pipes in syphons did not fail except at their connections with the reinforced concrete sections. It took 45 days to repair the aqueduct.

In the 1971 earthquake 353 fissures and cracks occurred at the same zones than in 1965, Ref. 5, the repairs lasting now 19 days; epoxic resines were now used speeding thus the process. In the meanwhile, more than 300 failures at the pipelines in Valparaíso and Viña del Mar had been repaired, but some were still undetected until the aqueduct was again in service. It took 5 more days to finish the repairs at the pipelines of the cities. Most of these failures occurred to asbest-cement pipes on streets that follow roughly the contour lines of hills and that were laid in fill. They were usually broken at the central part.

The other two sources of Peñuelas and Concón stayed for 2 and 3 days out of service. However, 40% of the population lives between 120 and 170 m. above the sea level and depend on Las Vegas system. They received water at a rate of 10 lit. a day per person during 24 days. Elevated and underground water tanks did not suffer damages.

The port of San Antonio and small ressorts north from the Maipo river are supplied from a plant at the river side. The central building subsided from 7 to 17 cm., damaging the pipes that come from the tanks and lateral buildings. No studies in soil mechanics had been conducted when the plant was designed, and it is feared that the consolidation is not yet finished.

The impulsion pipe, a steel pipe buried in the ground and surrounded by concrete, suffered 11 breaks in a longitude of 140 m. Water supply was interrupted for about two weeks.

RAILWAYS AND BRIDGES.

Damage to the railway system was observed in embankments abutments, bridges supports and some retaining structures.

Embankments : These are built with any material available near the construction site except clays and sand. No special soil mechanics study is done. Slopes 1,5:1 (h:v) are used. The soil is spread in 50 cm. thick layers and no special compaction method is used other than the machinery traffic. The width of the embankment is only enough for one track. Damages caused by the earthquake were longitudinal cracks and some completely developed slides that comprised part of the slope. Settlement was also observed, specially behind abutments which were often damaged. This kind of damage increased gradually closer to the epicentral area. The damages to embankments were rapidly repaired.

Bridges : Several railroad bridges suffered some damage in supports, piers, foundations and structural elements. The Maipo bridge located south of Santiago had the abutments and one pier foundation severely damaged. The last is a rock masonry block 10 x 5 x 3,5 m. that supports two 20 m. high steel structures, one for each track. The masonry block broke in the corners near the anchors of the steel structures.

The Quinquimo bridge, a few kilometers west of La Ligua suffered a lateral displacement of about 25 cm. This bridge is a steel simply supported structure. Many bridges had the same kind of problem in the supports. Sliding supports are built with four cylindrical rollers between 3 and 4 inches diameter. To avoid lateral displacement, the cylinders have a wider section both sides of the supports (Fig. 4). This wider part generally broke with the earthquake allowing the bridge to slide sideways. The same happened in several places with the fixed supports.

From La Ligua to Los Vilos the railway bridges are reinforced concrete built. They showed important damage to the diagonal beams that brace the piers corresponding to fixed supports. El Buitre bridge and El Chivato bridge 50 Km. south of La Ligua showed this kind of failure. The connections of two of such members broke. This damage did not interrupt traffic.

Santiago-Valparaíso route was closed 10 days mainly due to a slide in a cut which interrupted the tracks. The Illapel tunnel was closed because of the failure of the retaining walls at both ends of it.

ROADS AND BRIDGES.

Effects similar to those observed in railroads embankments ocurred in roads embankments and fills. Maximum settlements of about 30 cm.

occurred at the end of embankments in front of low bridges when no abutments were constructed. The longitudinal cracks and rock slides were observed as far as 100 Km. from the epicentral area but their frequency and importance increased closer to the epicenter.

A secondary road between Zapallar and Quintero was constructed partially on silty sandy slopes of steep gradient. Slides affected the part of the road built on fill. Another road built on sand dunes with some cohesion failed between Concón and Viña del Mar involving 3 houses in the slide. The vertical movement was about 80 cm. Several retaining structures failed in the same area. The same failures occurred in this place in 1965 earthquake. Slides occurred also in steep cuts in weathered granite, about 40 m. high, in the road entering Valparaíso.

A skew bridge located at Pullalli west of La Ligua suffered during 1965 earthquake the fall of one section of the superstructure, Fig. 5. The hinged connection had no protection against lateral or upwards displacement except for some steel bars connecting both slabs. After the earthquake the connection was improved by building reinforced concrete beams providing thus a continuous support, Fig. 7. In 1971 earthquake the same joint suffered a lateral displacement but the continuous support worked well. The north section, however, failed at a similar hinge where no reinforced concrete transverse beams had been provided, Fig.6. Other two sections of the superstructure fell down. It was found that the standard chilean design of seismic bars shown in Fig. 8 was incomplete. It had been neglected during the construction and part of the bars had been added later, welding them to the webs of the steel beams. The welded connection were broken by earthquake loads. Other factors in the failure were the fact of the bridge being skew, lossing support surface for rotations of the slabs about vertical axes; and large oscillations of piers founded on 13 m. deep caissons surrounded by very soft material.

A new bridge over the Maipo River by Santo Domingo, has 28 spans of 30 m. Superstructure sections are simply supported, built of prestressed concrete. No anchorage against lateral or longitudinal displacements or against upwards movement was provided. Every section moved though no one fell down. Maximum transverse displacement of 62 cm. and longitudinal displacements of 30 cm. were measured.

An overpass at Llay-Llay over the Santiago-Valparaíso railroad suffered damages in 1965 at the interior part of an arched pier, Fig.9. Stirrups were insufficient for preventing the curved main reinforcement to straighten under the seismic stresses. The same kind of damage, though more extense, occurred in 1971 earthquake, when also damages to abutments and handrails were observed.

PORTS.

The ports of Valparaíso and San Antonio serve the trade of the central zone of Chile, with 70% of the population of the country. No damages were observed in 1965; damages in 1971 to the quaywalls and warehouses disturbed their normal operation for many months. San Antonio Port, Fig. 10, has 3 sites for 18.000 Tons. ships plus other sites for smaller ships. Quaywalls 1 and 2 suffered tilting with maximum displacements of 60 cm. and subsidence of the backfill up to 60 cm. Cranes had to be fixed. A longitudinal crack, Fig. 10, was observed. Warehouses were heavily damaged and had to be demolished. A group of undamaged steel silos was disassembled in order to reduce the loads acting on the quaywalls. Site 2 was inactive for 6 months; site 1 was still inactive by December 1972; site 3 remodelling began before the earthquake and was not yet finished by that date.

In Valparaíso, site 1 and 5 and pier 8, Fig. 12, were operating with 18.000 Ton. ships; sites 6 and 7 were remodelled. Tilting of quaywalls 4 and 5 with maximum displacements of 5 cm. and subsidence of the backfill up to 40 cm. inmobilized trains. Semi-portal cranes were also fixed because of the separation of the rails. Warehouses at site 5 had to be demolished. After 17 months, site 4 is again in operation with fixed cranes; new warehouses at site 5 were not finished by December 1972. Site 6 enter into operation by that date. Other damages affected the quaywall between sites 5 and 6 and the front wall between sites 6 and 7, with displacements up to 30 cm.

These quaywalls were constructed in the period 1911-1930 without consideration of earthquake forces. After 1960, gravity quaywalls and sheetpiles bulkheads are designed for an horizontal acceleration of 0.2g.

CONCLUSIONS

Building structures designed according to the actual chilean codes behaved well. The design of reinforced masonry structures need however some improvement. Construction practice and supervision must be improved.

Water supply systems, bridges and quaywalls should be designed taking into account the recommendations of the Japanese Society of Civil Engineers. Most of the damages observed in those structures could have been avoided with this consideration.

Stability of slopes during earthquakes should also be seriously considered when designing roads or buildings.

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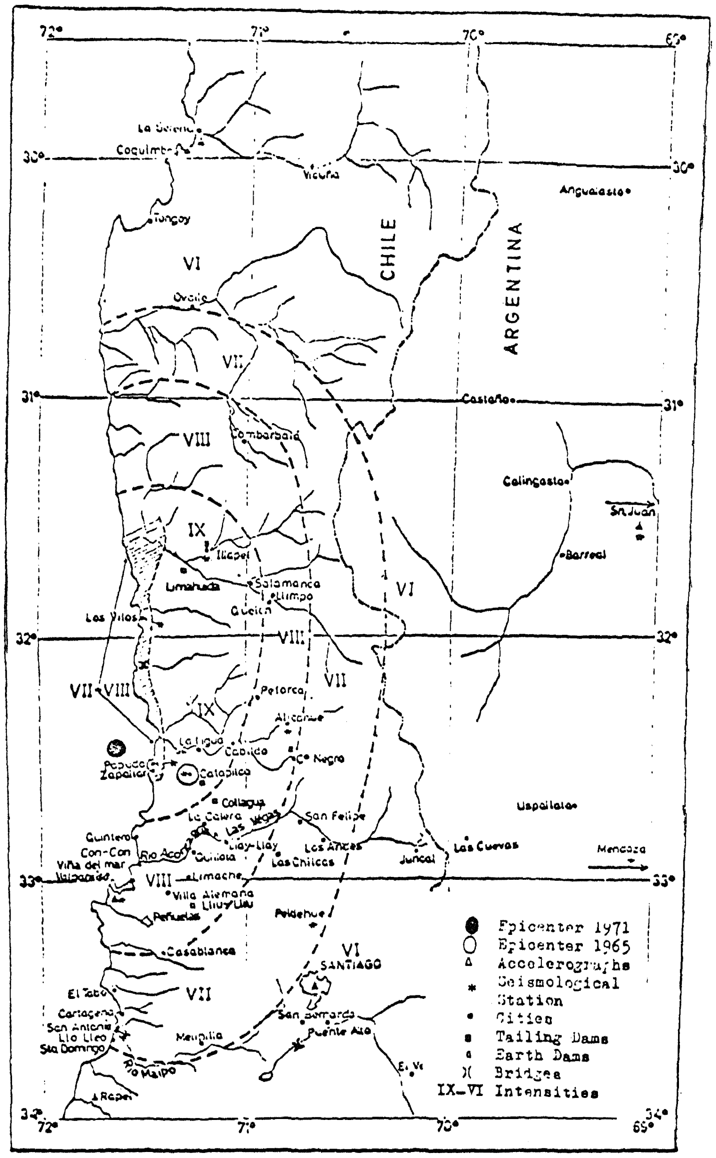


FIG. 1 LOCATION MAP

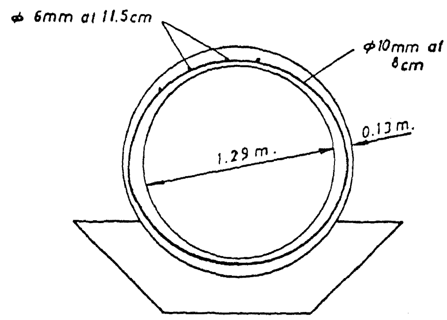
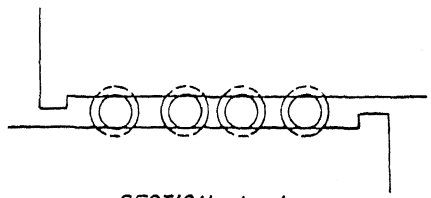


FIG. 3 SECTION OF LAS VEGAS AQUEDUCT



SECTION A - A

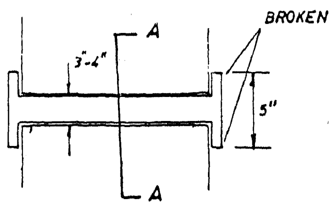


FIG. 4 SLIDING SUPPORTS OF RAILROAD BRIDGES

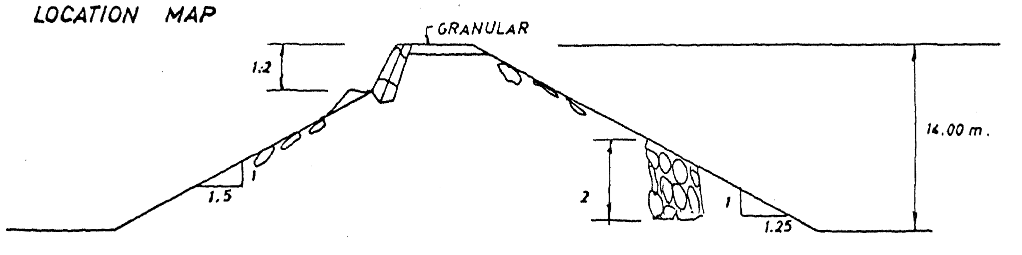


FIG. 2 TIPICAL SECTION CATAPILCO DAM

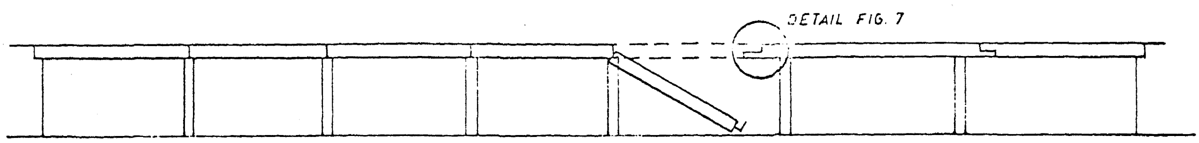


FIG. 5 PULLALLI BRIDGE 1965

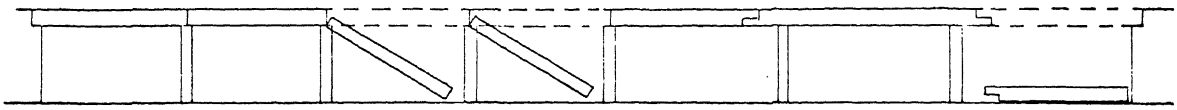


FIG. 6 PULLALLI BRIDGE 1971

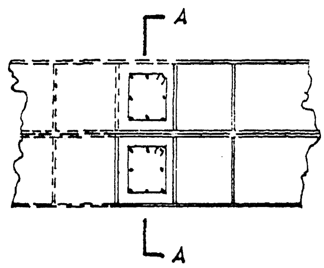
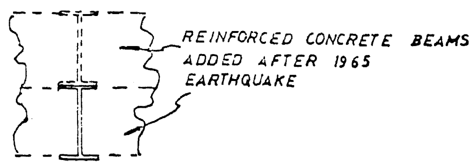


FIG. 7 DETAIL



SECTION A-A

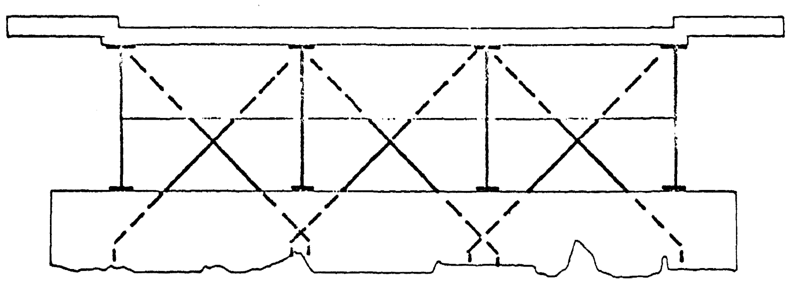
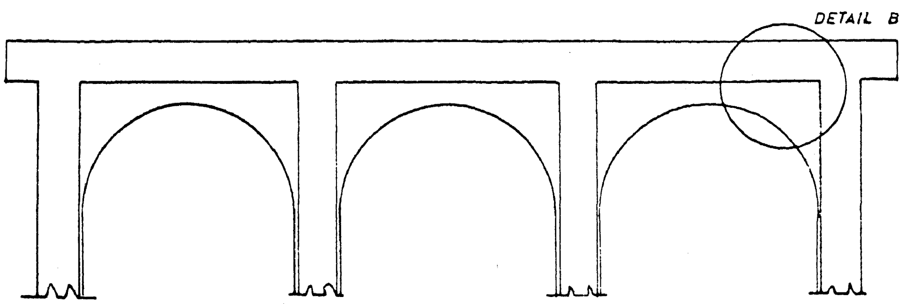
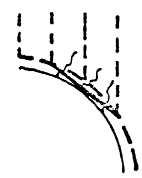


FIG. 8 DETAIL OF SEISMIC BARS DISPOSITION





DETAIL B

FIG. 9 DETAIL OF ARCHED PIER LLAY-LLAY OVERPASS

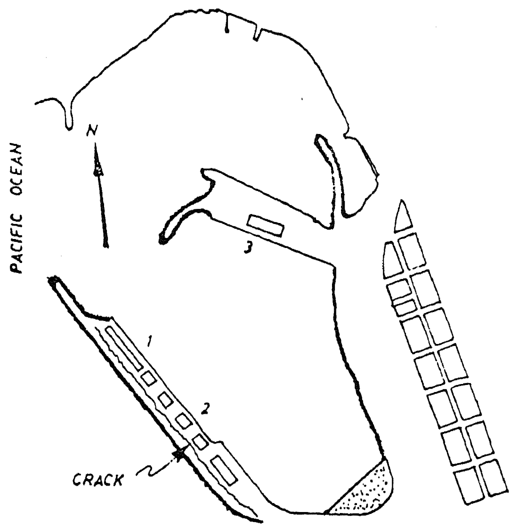


FIG. 10 PORT OF SAN ANTONIO

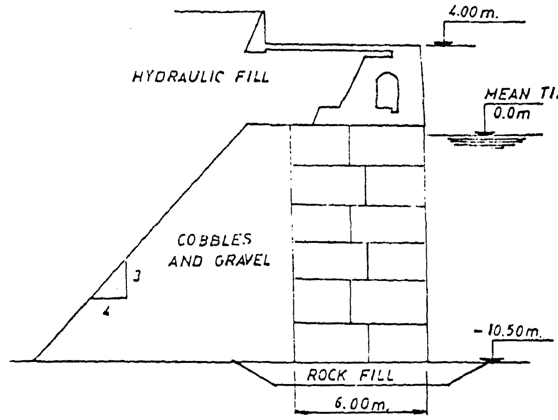


FIG. 11 QUAYWALL AT SITES 1,2 SAN ANTONIO

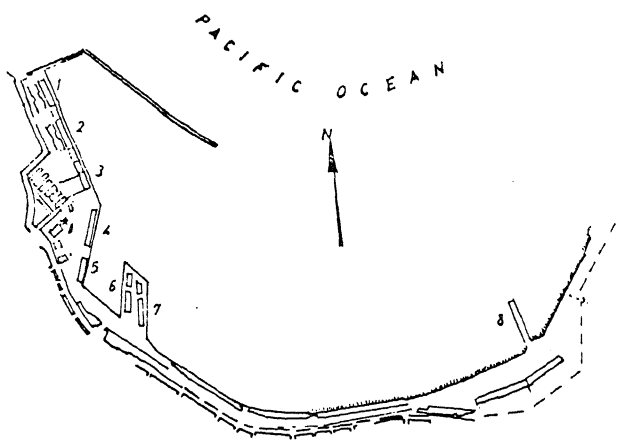


FIG. 12 PORT OF VALPARAISO

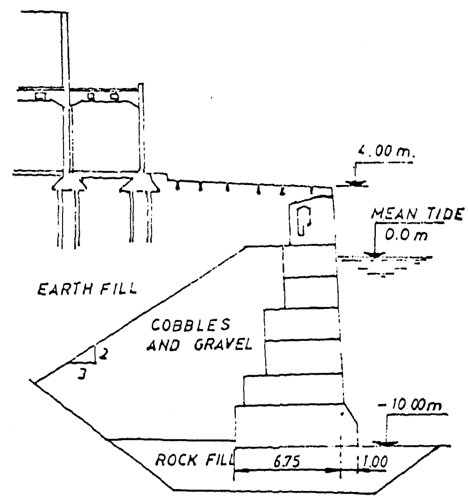


FIG. 13 QUAYWALL AT SITES 1,2,3,4,5 VALPARAISO

SAFETY FACTORS ($\phi = 35°$; $c=0$; $\gamma_s = 2.2$; low tide)

	Sliding			Bearing capacity		
k	0	0.1	0.2	0	0.1	0.2
San Antonio 1,2	1.9	1.1	-	1.8	< 1	-
Valparaíso 1-5	2.0	1.2	0.8	4.4	3.5	1.5
Valparaíso 8-7	2.2	1.2	0.9	6.9	4.4	2.4