VIBRATORY COMPACTION OF THE SOIL AND TECTONIC SUBSIDENCE DURING THE 1960 EARTHQUAKE IN VALDIVIA, CHILE

by

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SYNOPSIS

Careful levellings in the city of Valdivia made before and after the earthquake, and data from first order levellings made in 1959 and 1963 by the Geographical Institute of the Army between 39°S and 41°S and located in different types of soils and rocks, are analyzed. Some index properties of the soil were determined by borings and soil tests made by the Soil Mechanics Division of IDIEM[III] since 1960. Depth of basement rock was obtained by means of gravity survey.

The amount of regional tectonic subsidence and settlement due to vibratory compaction for a large number of points in the city was calculated.

The results are discussed and some probable causes of the subsidence are suggested.

INTRODUCTION

IDIEM began at the end of 1965 a systematic study of the Valdivia subsoil in order to correlate its properties with the damages caused by the May 1960 earthquake and to prepare the microzoning of the city. This study was called "Plan Valdivia"

The first step of this study was oriented to the gathering of field data connected with 1) the magnitude and distribution of settlements, 2) relations between soil type and damage on buildings, and 3) study of the geology, origin of the soil, identification of clay minerals, determination of the velocity of shear waves, etc. The next step, now starting, involves the interpretation of field data.

This paper presents the results related with the separation of the total subsidence occurred in Valdivia into: Tectonic Subsidence and compaction by vibration.

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SOME NOTES ABOUT THE URBAN[8,9] AND SEISMIC HISTORY OF VALDIVIA[7,12]

Valdivia, the oldest austral city in the world, was founded by the spanish explorer and conqueror Pedro de Valdivia in 1552. It was located on a rather plane hill of about 15 to 16 m. high, surrounded by rivers, ponds and low flooded areas (Fig. 1 and 2A). It was called "The City of the Lake" because it was accessible only by two points.

At the end of the XVI Century, Valdivia had more than 450 houses built mainly with slate, wood and roof-tiles; streets paved with stones, two markets, several public buildings including two large churches and three convents. During this century it was seriously affected by the 1575[I] earthquake and tsunami and flooded in 1576 by the sudden rupture of a natural dam formed below the Lake Riñihue by landslides of the previous earthquake. In 1599 the city was completely destroyed and ransacked by the indians.

In 1578, it was ordered to move the city to the Mancera Island in the Corral Bay. In 1779 Valdivia was again translated to its old and actual location. Figure 2B shows a general view of the city, including the position of two towers in fortresses built in 1774 and which still stand in good conditions. Figure 3A shows the general disposition in 1798.

In 1850 Valdivia (3000 inhabitants) began a fast expansion mainly due to the arrival of german immigrants. A large number of industrial, commercial and cultural activities were created. Among them two universities, shipyards, a steel plant, a large brewery, a shipline, shoe factories, distilliries, wood and meat processing industries, etc. Fig. 3B shows a plant view of the city at the end of the XIX Century. In 1960 the city had a population of 72.400.

ARTIFICIAL FILLS IN THE CITY

According to borings made by IDIEM it was possible to establish a maximum thickness of artificial fill of about 3 m covering the old low areas shown in the previous figures. In this study some areas in which the thickness was probably larger (the water front area) were not included.

There are two main fill areas. One in the northern part of the city with boot-shape form and the second in the southern part, beginning at the corner of Arauco and Camilo Henríquez Streets (Fig. 4) and becoming broader towards the south.

After the 1909 fire the soil surface of the central and higher area of the city was lowered and flattened in order to decrease the slope of the streets (Fig. 4). The differences shown in this figure were obtained by comparison of the sewage chamber levellings of 1911 and 1924 with a levelling made in 1959. The fills were deposited without controlled compaction. The materials are mainly silty soils, classified as ML to MH according to the USCS.

(I) According to the chroniclers it was extraordinarily similar to the 1960 earthquake.

All these fill areas were strongly correlated with the damage caused by the 1960 earthquake, but they were not so important in connection with compaction, as will be seen later.

GEOLOGY OF THE REGION

The oldest rocks (Precambrian or early Paleozoic) found in the Valdivia region correspond to metamorphic rocks, principally phyllites and schists. They are exposed extensively along the coast from Concepción (Lat. 37°S) to Chiloé Island (Lat. 43°S) and constitute the main element of the Coastal Range. The metamorphic rocks are intruded in some places by granitic rocks. Some outcrops can be found near the city of Valdivia.

The rock units already mentioned are in some places covered by Tertiary sedimentary deposits, mainly sandstones and shales. These outcrops are normally small in size but are disseminated in a large area.

Metamorphic rocks, granits and Tertiary marine sediments have been covered since Quaternary by fluvio-glacial deposits with some intercalations of sediments of marine origin. These sediments constitute the most important rocks of the Valdivia basin. Fig. 5 shows the general Geology of the region according to the Geologic Map of Chile prepared by the Institute of Geologic Research (I.I.G.).

The Quaternary sediments of Valdivia are of fundamental importance for the understanding of the mechanism of subsidence during the earthquakes of May 1960. According to recent studies, these sediments, composed by irregular beds of silt, sand and gravel of marine and continental origin, correspond to material deposited by the Valdivia river and subsidiaries, and by sediments laid down during changes of sea-level occurred in Glacial and post-glacial periods.

The thickness of Quaternary sediments can be seen in Fig. 6B. It shows a Bouguer gravity profile across the Valdivia Basin and the corresponding interpretation with a density contrast of 0.5 g/cm^3. The maximum calculated thickness is about 340 m.

It is not the aim of this paper to give a detailed description of the soil of Valdivia, however it has been found advisable to present a soil profile through the main part of the city in order to give a general idea about the soil classification and soil characteristics (Fig. 7). This profile has been based on borings made by the Soil Mechanics Division of IDIEM since 1961.

TECTONIC SUBSIDENCE

The earthquake of May 22, 1960 (Lat. 39.5°S, Long. 74.5°W, depth 60 Km., M = 8.4) modified considerably the topography in an area between latitudes 37°S and 43°S. This can be observed specially along the coast from Concepción to Chiloé Island. Part of these changes were caused by landslides, compaction by vibration, effects of the tsunami that followed the earthquake, and tectonic subsidence. Many authors have analyzed these changes, among others [2,3,5,10,14,15,18]. There is general agreement about the existence of large tectonic movements that can be observed specially along the coast. From Puerto Saavedra (Lat. 39°S) to Chiloé Island

(Lat. 43°S) a subsidence of 1-2 meters is clearly visible by simple comparison of the sea level before and after the earthquake. North of Puerto Saavedra an uplift of about one meter affected the continent between Lat. 37°S and 38½°S. Islands off the coast of Chile between 37°S and 43°S (Mocha and Guafo) were also uplifted about 1-1.5 meters (Fig. 8. It has been suggested[15] that the line separating uplifts and subsidences, with a trend approximately N-S, located off the coast along the axis of the aftershock epicentral area, may represent the position of a fault activated during the great earthquake (Fig. 8). This is also supported by the P and S fault plane solutions and by application of the theory of the radiation pattern of moving sources[13]. [4,13] show also that the faulting was progressive from North to South.

In the Valdivia region (Lat. 39.5°S) the subsidence was more severe than in the rest of the damaged area[3,15], as it should have been expected according to the location of the epicenter of the main shock.

A comparison of geometric levellings along the Panamerican Highway from Temuco (Lat. 39°S) to Puerto Montt (Lat. 42°S) made by the Geographical Institute of the Army in 1959 and 1962, makes the calculation of the tectonic movements possible along a line approximately 50 Km. from the coast. Fig. 5 shows the total subsidence occurred along the Highway. The road runs mainly on three types of materials: 1) Quaternary sediments of the Central Valley with thicknesses that range between 500 and 2000 m, 2) Metamorphic rocks, 3) Quaternary sediments of the Valdivia Basin.

The Quaternary sediments of the Central Valley and Valdivia Basin are quite different in composition and origin. The former is mainly composed of fluvio-glacial sediments with important intercalations of volcanic material and constitute, in general, a good basis for the foundation of civil engineering structures; the latter is a combination of silts, clays, and sands of continental and marine origin with high water content and organic material. The subsidence in this soil during the earthquake of May 22, 1960 is undoubtedly a combination of tectonic subsidence and compaction due to vibration as will be seen later. In order to separate both types of subsidence the following criteria was considered:

a) Subsidence determined in granitic and metamorphic rocks is of tectonic origin.

b) The tectonic subsidence is of regional character and therefore, local differences in the amount of total subsidence have to be attributed to compaction by vibration or some other cause.

c) The tectonic subsidence is largest close to the location of the epicenter (Lat. 39.5°S) and gradually diminishes to the North and South.

d) The tectonic subsidence probably diminishes from the coast inland. This can be seen in Fig. 5 where the total subsidence along the road is intimately related with the distance to the coast.

e) The composition and origin of the Quaternary sediments of the Central Valley and the regularity of the variations of the subsidence in this soil, indicate that a very small proportion of the total subsidence in this material is due to compaction, large slumping in old fill areas, landslides, etc.

f) Subsidence along the coast determined by different authors were measured in granitic and metamorphic rocks, and therefore they have to be considered as being of tectonic origin.

g) If a fault is responsible of the May 22 earthquake, it must be located off the coast of Chile because i) epicenter location, ii) distribution of subsidence and uplifts along the coast and islands (Fig. 8), iii) the earthquake was followed by a severe tsunami.

h) Total subsidence in Valdivia is very irregular, ranging between 1.8 m and 2.6 m (Fig. 9) in an area which is very small (5 Km x 5 Km) compared to the area affected by tectonic movements (at least 700 Km x 50 Km). In this scale, the tectonic subsidence in the city of Valdivia may be considered as having a constant value, and therefore the irregularities have to be attributed to compaction by vibration or other causes.

Close to the southern border of the Valdivia Basin, bench mark 3H83, the subsidence on metamorphic rock was 1.81 m. This value is representative of the regional tectonic subsidence of Valdivia, since it is close to the city and at approximately the same distance from the coast as Valdivia. Bench mark 2H32 with a subsidence of 1.86 m is in similar conditions to the north of the basin. Total subsidence in the city itself, ranges between 1.8 m and 2.6 m. If it is considered that the minimum values represent tectonic subsidence without compaction, it can be followed from h) that the tectonic subsidence in the city of Valdivia is of the order of 1.8 m. This is ratified by d) and f), since [3,10] and [17], consider that the tectonic subsidence along the coast, reaches its maximum at the latitude of this city, and give values ranging between 1.5 and 2.5 m.

Taking the value of 1.8 m as tectonic subsidence in Valdivia and according to criteria a) to g) the curve of tectonic movements along the Panamerican Highway (Fig. 5) was traced. The increase of the slope of this curve starting at Lat. 39.4°S and Lat. 40.3°S is due to d).

VIBRATORY COMPACTION OF THE SOIL

For estimating the non tectonic part of the subsidence of the soil during the 1960 earthquake the data from precision levellings of the city were used.

[6], levelled all street corners of Valdivia in a work done for the Department of Sanitary Engineering of the Ministry of Public Works in 1959.

[16], made a similar high precision levelling in order to design the new sewage system of the city in 1962.

These data were compared with bench marks installed by the Geographical Institute of the Army and reduced to the same origin (mean sea level in Valparaíso). The information was also checked with considerable field work.

The difference between total subsidence and tectonic subsidence (Fig. 9) has to be explained as caused by large slumping in old fill areas, landslides, irregularities in the tectonic subsidence pattern, compaction by vibration, or some other cause.

Slumping in old fill areas cannot be the principal cause. Careful studies indicate no correlation between the non-tectonic subsidence pattern and location of fill areas.

Large landslides are observed only outside the city (Riñihue lake, etc.). Level points inside the city which could have been affected by local landslides or slumpings as the points extremely close to the water front, were omitted.

Irregularities in the tectonic subsidence pattern are improbable, (page 6g and 7h).

The non-tectonic subsidence has to be explained as due to compaction by vibration or some other cause not fully understood. The authors consider that the most probable cause is vibratory compaction. It is interesting to note that there were no evidences of liquefaction during the earthquake. However large amount of gas emanated in some places during the drillings for soil studies at depths between 12 m and 20 m. Part of this gas may have escaped or compressed allowing the settlement of the soil.

For getting the amount of compaction, the tectonic subsidence, assumed to be 1.8 m, was substracted from the total subsidence. These differences, ranging between 0 and 0.8 m, are presented in Fig. 9.

CONCLUSIONS

It is suggested that the tectonic subsidence due to the earthquake of May 22, 1960 was maximum at the latitude of Valdivia reaching there a value of about 1.8 m. It diminishes gradually to the north, south, and inland. Islands off the coast of Chile and the Arauco Península suffered an upheaval of about 1-1.5 m. This can be interpreted as being caused by a fault about 1000 Km long with a trend approximately NS located off the coast with a positive movement of the western block and a subsidence of the eastern block. The continental block seems to have a maximum subsidence close to the fault and gradually diminishes inland reaching a value of about 0.5-0.8 m at a distance of around 50 Km from the coast. No measurements along transversal roads were done after the earthquake, thus it is not possible to know at which distance from the coast the Chilean territory was not affected by tectonic movements. If an EW slope of 1 m subsidence per 50 Km horizontal distance is considered according to the mean values along the coast and Panamerican Highway, the tectonic movement would have affected a continental strip of about 100 Km width.

The enormous areal extension affected by the tectonic movements, compared with the size of the city of Valdivia, allows to make the assumption that the tectonic subsidence of Valdivia was uniform and of about 1.8 m. The differences between this value and the values of total subsidence measured in the city must be interpreted as being due to compaction by vibration of the Quaternary sediments of the Valdivia Basin.

There is a lack of information in current literature about compaction caused by seismic vibrations in large soil areas under natural conditions. This paper intends for the first time to give a real evaluation of the existence of large settlements due to compaction caused by earthquakes.

The main objective has been to show that this compaction is possible. Values of the order of a meter have been determined.

The mechanisms and conditions of the soil to cause the compaction are not evident at this stage of the research. However, some general conclusions have been obtained which can be summarized as follows:

- The damages were highly concentrated in the artificial fill areas of Valdivia. The behaviour of these areas was not important in connection with compaction.

- The amount of compaction ranged between 0 and 0.8 m with a common magnitude between 0.15 and 0.45 m. Similar settlements may have occurred in previous earthquakes.

- There is no observable correlation between type of soil and compaction.

- No evidence of liquefaction was observed.

- It is possible that below the water table, part of the soil was only partially saturated. If this is so, it may have been caused by the presence of swamp gases which were detected in several borings at depths between 12 and 20 m. These gases may have been escaped or compressed allowing the settlement of the soil. This may also explain the detection of an unusual smell felt by some people of the region shortly after the earthquake.

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The present work has been made possible by the joint efforts between the Soil Mechanics Division of IDIEM and the Departments of Geophysics and Civil Engineering of the University of Chile. An important contribution was made by Ignacio Mena [11] and Ismael Rengifo [11] who collected and analyzed the main part of the data.

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BIBLIOGRAPHY

1. Aki, K. "Further Study of the mechanism of Circumpacific Earthquakes from Rayleigh Waves", J.G.R. v.65 pp. 4165-4172, 1960.

2. Alvarez, L., "Informe sobre los estudios realizados en la Zona comprendida entre la Península de Arauco y Valdivia, con motivo de los sismos ocurridos el 21 y 22 de Mayo de 1960", Publication Instituto de Investigaciones Geológicas, Chile, 1960.

3. Alvarez, L., "Studies made between Arauco and Valdivia with respect to the Earthquakes of May 21 and 22, 1960", BSSA v. 53, 1963.

4. Benioff, H., Press, F., and Smith, S., "Excitation of Free Oscillations of the Earth by Earthquakes", J.G.R., v. 66 pp. 605-618, 1961.

5. Doyel, W., A. Moraga and E. Falcon, "Relations between the Geology of Valdivia, Chile and the Damage produced by the Earthquake of May 22, 1960", BSSA v. 53, 1963.

6. García, A., "Tablas y Monografías de nivelaciones de Valdivia", DOS, Ministerio de Obras Públicas, 1959.

7. Greve, F., "Historia Sísmica de Chile", Publication Department of Geophysics and Geodesy, University of Chile.

8. Guarda, F., "Historia de Valdivia", Editorial Cultura, 1953.

9. Guarda, F., "Influencia Militar en las Ciudades del Reino de Chile", Academia Chilena de la Historia, Universidad Católica de Chile, 1967.

10. Housner, G.W., "An Engineering Report on the Chilean Earthquakes — of May 1960", BSSA, v. 53, pp. 219 - 223, 1963.

11. Mena, I., and Rengifo, I., "Estudio de una posible consolidación por vibración en el subsuelo de Valdivia durante el terremoto de 1960", Thesis, University of Chile, 1967.

12. Montessus de Ballore, F., "Servicio Sismológico de Chile", Anales Universidad de Chile, Tomo CXXV, 1909.

13. Press, F.A., Ben-Menahem and Toksöz, "Experimental Determination of Earthquake Fault Length and Rupture Velocity", J.G.R. v. 66 Nº 10 pp. 3471 - 3485, 1961.

14. Ruiz, F. and P. Saint-Amand, "Observations concerning the Chilean Earthquake of May 1960", Report XXI International Geol. Congress, Part XXVI pp. 116 - 133, Copenhagen, 1961.

15. Saint-Amand, P., "Los Terremotos de Mayo de 1960", US Naval Ordenance Test Station, Techn. Article 14, NOTS TP. 2701, 1961.

16. Von Bennowitz, J., "Mejoramiento Alcantarillado de Valdivia; Redes Existentes y Proyectadas; Aguas Servidas", Map of DOS, Ministerio de Obras Públicas, 1962.

17. Watanabe, I. and Karzulovic, J., "Los Movimientos Sísmicos de Mayo de 1960 en Chile", Instituto de Geología, Universidad de Chile, Publ. N° 14, 1960.

18. Weischet, W., "Further Observations of Geologic and Geomorphic Changes Resulting from the Catastrophic Earthquake of May 1960 in Chile", BSSA v. 53, pp. 1240, 1963.

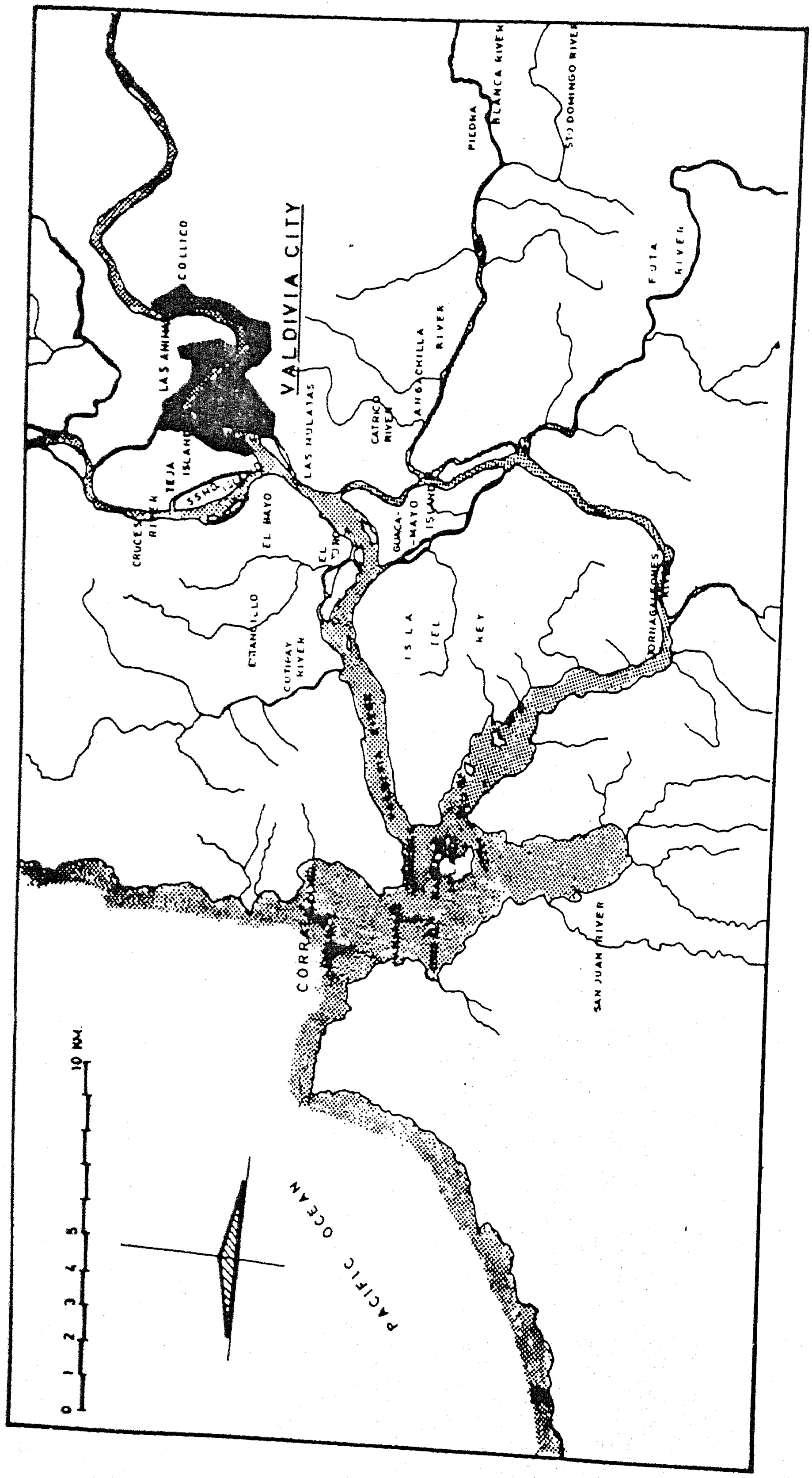


FIG.1
LOCATION OF VALDIVIA

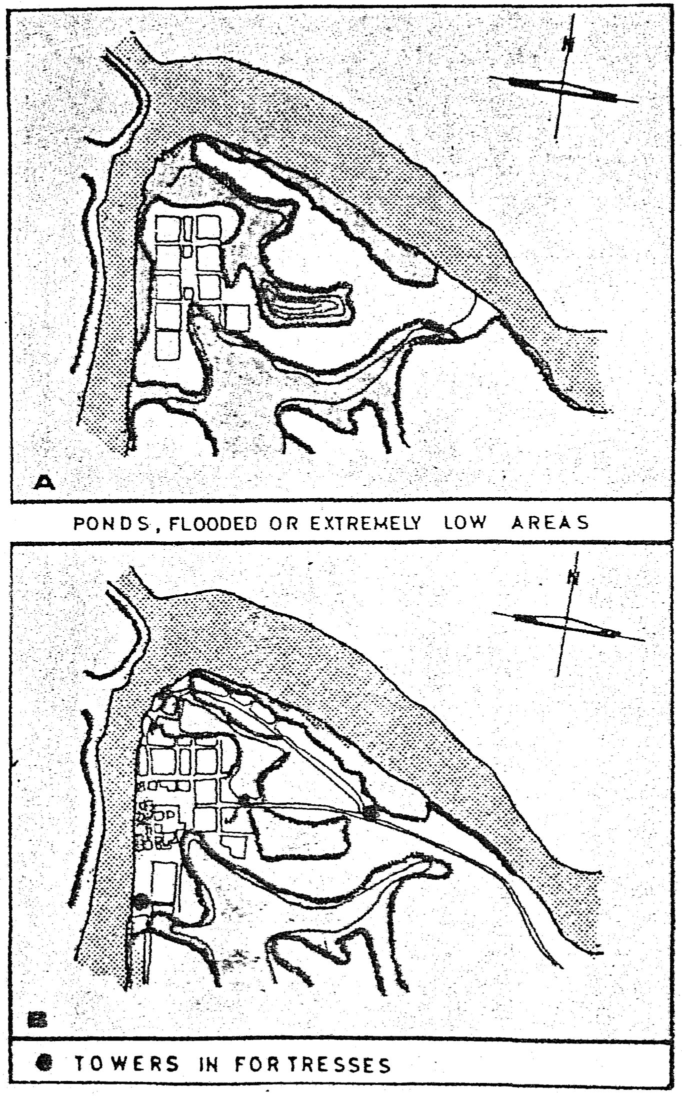


FIG. 2

A: VALDIVIA IN THE XVI CENTURY
B: VALDIVIA IN 1760

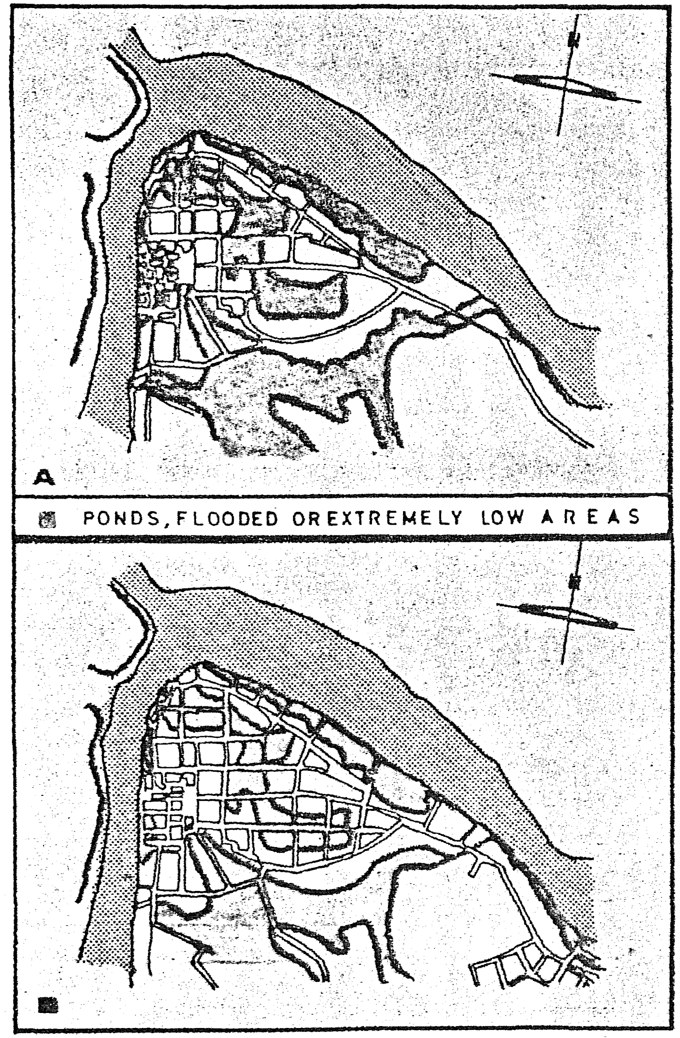


FIG. 3

A: VALDIVIA IN 1796
B: VALDIVIA AT THE END OF THE XIX CENTURY.

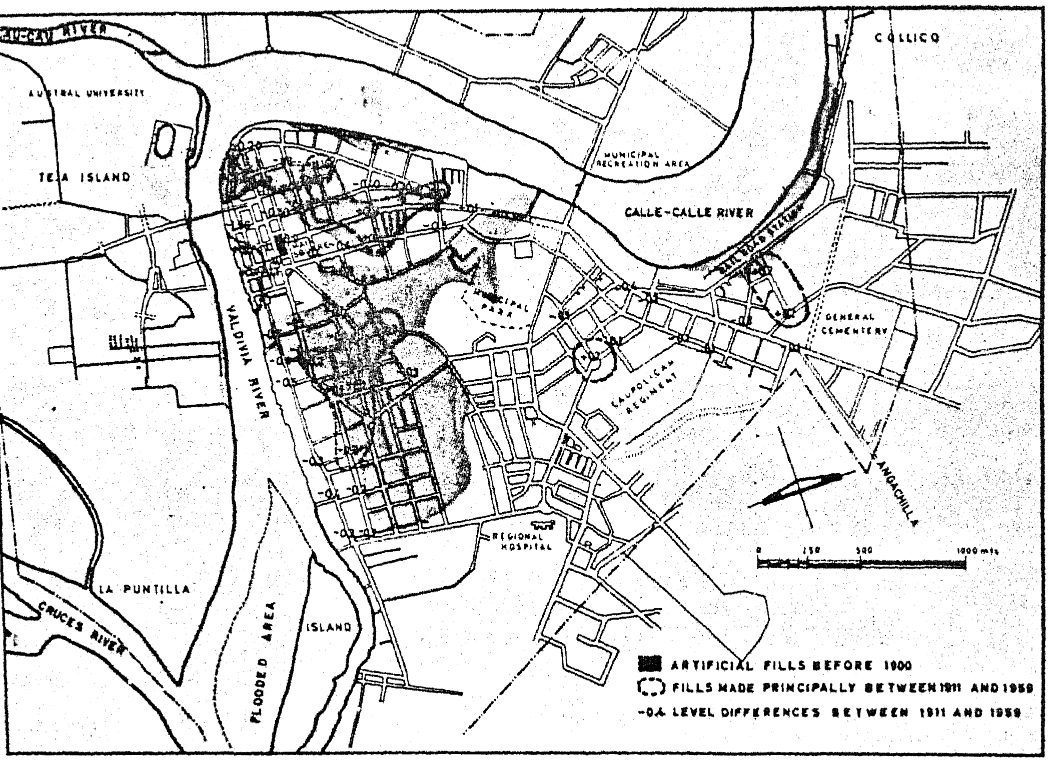


FIG. 4

ARTIFICIAL FILLS IN THE CITY BEFORE THE 1960 EARTHQUAKE

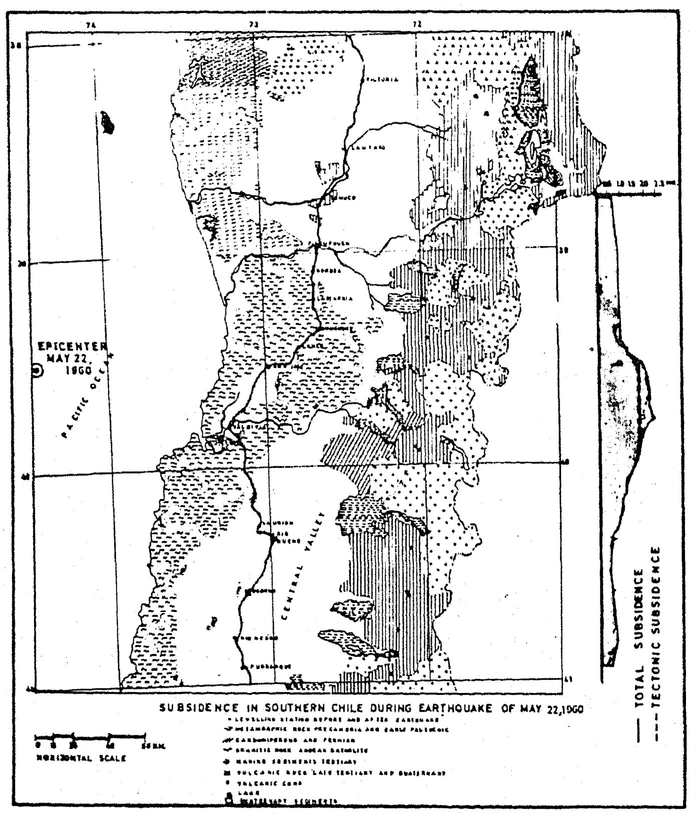


FIG. 5

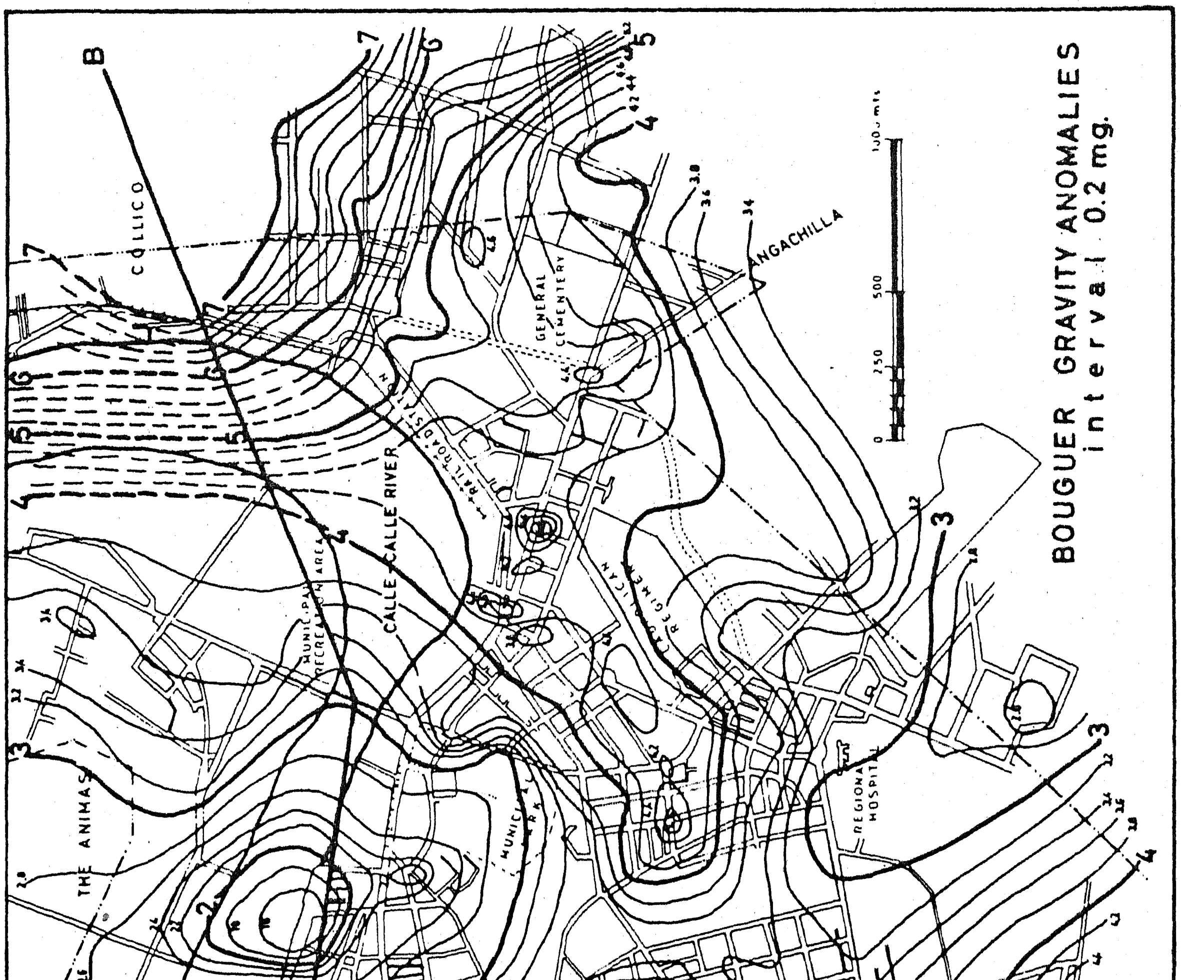

BOUGUER GRAVITY ANOMALIES
interval 0.2 mg.
COLLICO
ANGACHILLA
GENERAL CEMENTERY
CALLE-CALLE RIVER
MUNICIPAL RECREATION AREA
THE ANIMAS
REGIONAL HOSPITAL
VALDIVIA RIVER
FLOODED AREA
ISLAND
LA PUNTILLA
CRUCES RIVER
TEJA ISLAND
AUSTRAL UNIVERSITY
B
A

FIG. 6A

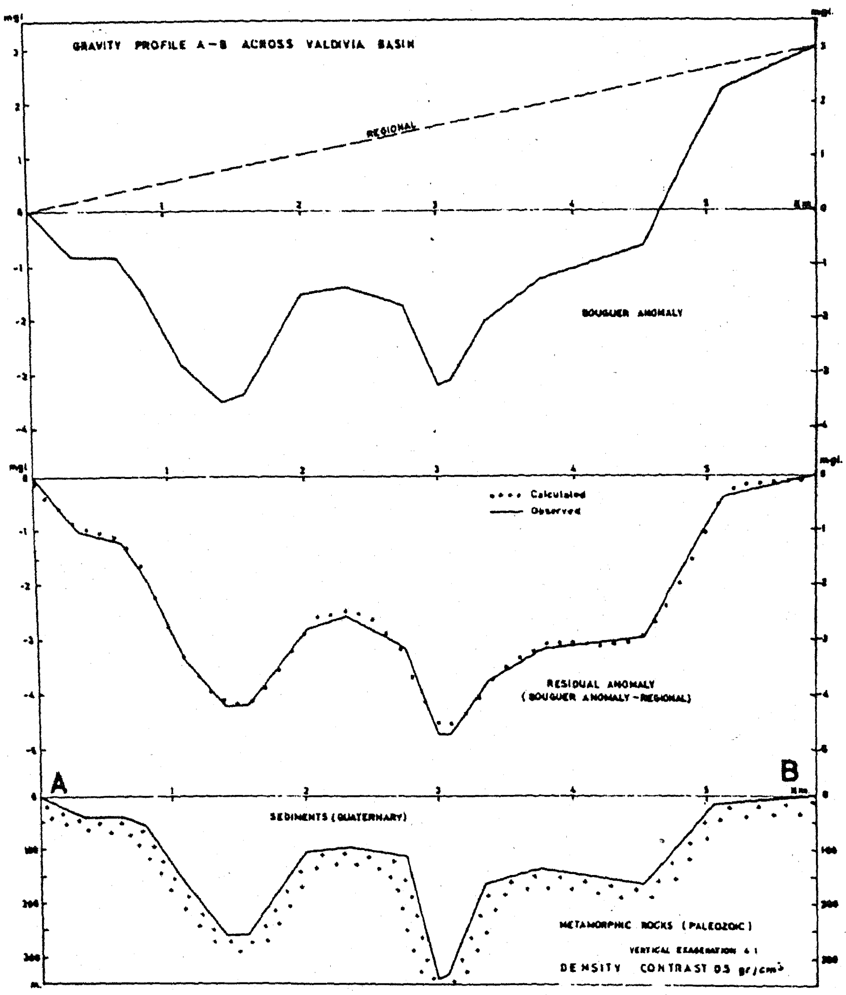
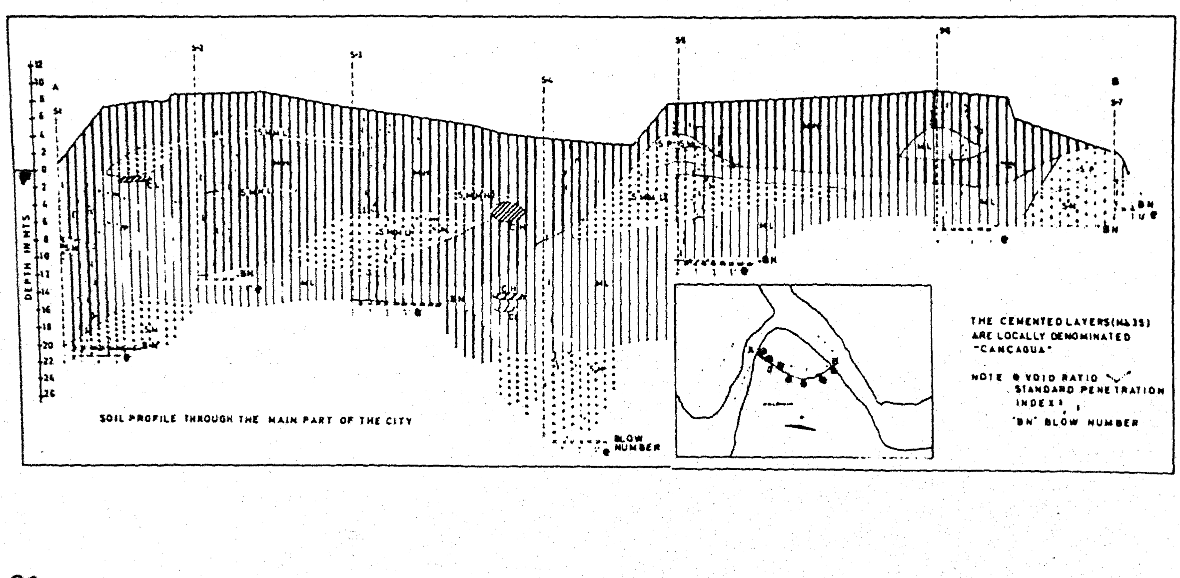
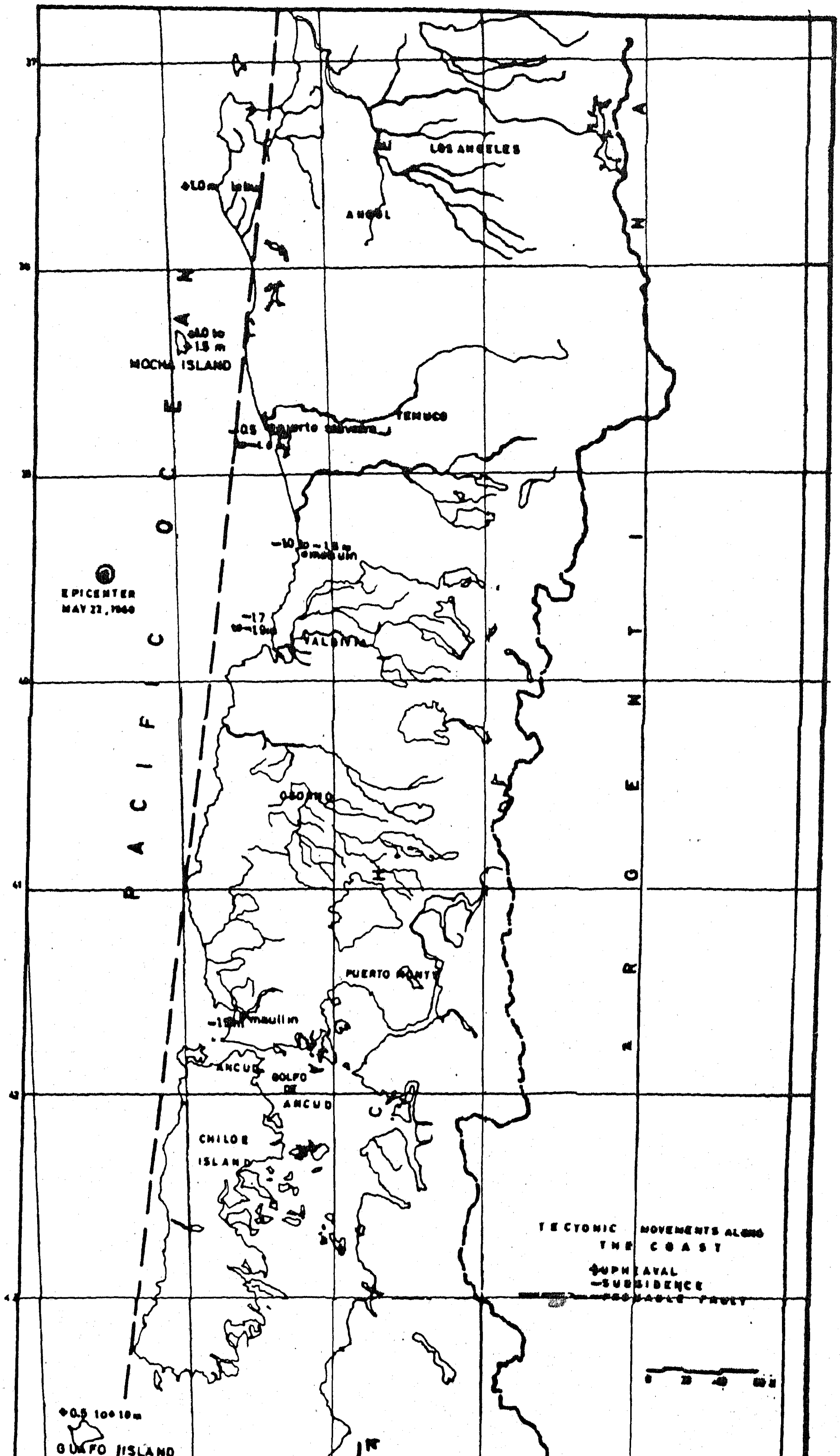

GRAVITY PROFILE A—B ACROSS VALDIVIA BASIN
REGIONAL
BOUGUER ANOMALY
Calculated
Observed
RESIDUAL ANOMALY
(BOUGUER ANOMALY - REGIONAL)
A
B
SEDIMENTS (QUATERNARY)
METAMORPHIC ROCKS (PALEOZOIC)
DENSITY CONTRAST 0.5 gr/cm³

FIG. 6 B


DEPTH IN MTS
SOIL PROFILE THROUGH THE MAIN PART OF THE CITY
BLOW NUMBER
ARE LOCALLY DENOMINATED "CANCAGUA"
STANDARD PENETRATION INDEX
"BN" BLOW NUMBER



LOS ANGELES
ANGOL
MOCHA ISLAND
TEMUCO
EPICENTER
MAY 22, 1960
VALDIVIA
OSORNO
PUERTO MONTT
maullin
ANCUD
GOLFO DE ANCUD
CHILOE ISLAND
GUAFO ISLAND
PACIFIC OCEAN
ARGENTINA
TECTONIC MOVEMENTS ALONG THE COAST
+UPHEAVAL
−SUBSIDENCE

FIG 8

A-5

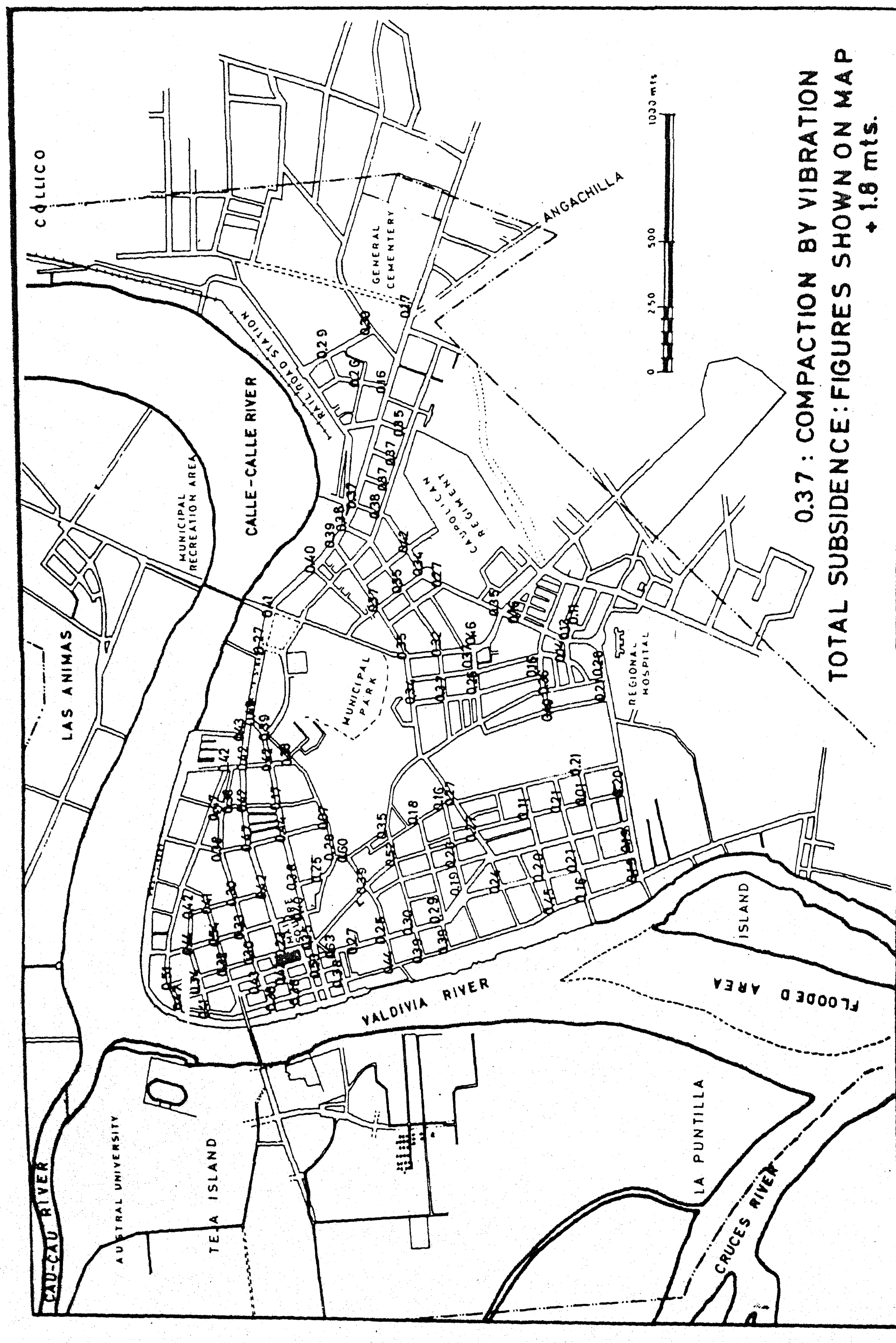

0.37 : COMPACTION BY VIBRATION
TOTAL SUBSIDENCE: FIGURES SHOWN ON MAP
+ 1.8 mts.
0 250 500 1000 mts
COLLICO
ANGACHILLA
GENERAL CEMENTERY
RAILROAD STATION
CALLE-CALLE RIVER
MUNICIPAL RECREATION AREA
LAS ANIMAS
CAUPOLICAN REGIMENT
MUNICIPAL PARK
REGIONAL HOSPITAL
VALDIVIA RIVER
ISLAND
FLOODED AREA
AUSTRAL UNIVERSITY
TEJA ISLAND
LA PUNTILLA
CRUCES RIVER
CAU-CAU RIVER

FIG. 9