Foundations of Buildings Subject to Seismic Forces

Fondations d'édifices soumis à des secousses sismiques

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Summary

The paper presents details of the foundations of nine buildings designed by the Ministry of Works over the past six years.

The techniques employed to transmit seismic forces to the foundations are given.

Foundations are described and various problems of a seismic design illustrated by example.

The design methods used are compared with :

(1) Design codes of other seismic areas.
(2) Results of research into soil properties.
(3) Results of surveys of building damage in earthquakes.

Sommaire

Ce mémoire donne des détails sur les fondations de neuf édifices, selon des plans établis par le Ministry of Works pendant les six dernières années, et mentionne les techniques employées pour transmettre les forces sismiques aux fondations. Il donne également la description des fondations et indique les divers problèmes rencontrés en les illustrant par des exemples. Les méthodes de construction sont comparés avec :

1) Les normes de construction utilisées dans d'autres régions sismiques.
2) Les résultats de recherches concernant les caractéristiques du terrain.
3) Les résultats d'études de dégâts causés aux bâtiments par les tremblements de terre.

Introduction

The nine buildings listed in Table 1 and shown in the diagrams have been designed in the Structural Design Office of the Ministry of Works in the last six years. All these buildings are in the four main centres, Auckland (175° E, 37° S), Wellington (175° E, 41° S), Christchurch (173° E, 44° S) and Dunedin (171° E, 46° S).

The three buildings in Auckland are founded on Tertiary deposits of lightly cemented sandstones and mudstones known locally as the Waitemata Beds. These deposits cover large areas of the North Island of New Zealand. Unconfined compression tests carried out on the upper layers of these beds gave strengths of from 10,000 to 40,000 lb. per sq. ft. These rocks are covered in the city area by clays up to 40 feet deep. The clays have low compressive strengths and are highly compressible. Although all the buildings described are founded on the Waitemata Beds three different foundation types are used.

The capital city Wellington, sited at the southern tip of the North Island, lies partly on the narrow foreshore of Port Nicholson but the majority of the city is on the surrounding hills. These hills are part of the great chain of Permian Greywacke rocks which runs through both Islands. In the Wellington city area deep deposits of decomposed greywacke have been transported to their present site, uplifted through almost a thousand feet and have subsequently eroded by hundreds of feet. The present surface materials are pre-consolidated by as much as 40,000 lb. per sq. ft. (C. M. Strachan, 1959). All the buildings described are sited on this preconsolidated material on a variety of foundation types.

The two South Island buildings described are both founded on a gravel stratum in recent deposits of clays, silts, sands and gravels. The Christchurch site lies on the Canterbury plains at this point some 40 miles in width. These plains are the product of weathering of the greywacke of the Southern Alps.

The Dunedin site is on recent estuarine deposits. The silts in these deposits have a high natural moisture content and building damage due to settlement is not uncommon in this area.

Design of superstructure

The design of the superstructure to resist horizontal loads due to seismic forces has a very marked effect on the distribution of load to the foundations. Since 1950 it has been common practice in the Ministry of Works to use, wherever possible, shear walls to resist these forces. These so called shear walls are in fact in tall buildings such as 1,5 and 9 subjected to heavy bending stresses. This approach to aseismic design has the advantage that the shear walls provide an economical protection to such features as cladding and glazing from earthquake damage, by keeping inter-storey deflection small.

The shear walls may be used externally as in buildings 7 and 8 or internally as in buildings 1, 2, 3 and 5. The latter method gives an unobstructed external perimeter for glazing, if required. A further development is shown in building 9 where the walls have been joined together to provide a central core.

Where transverse traffic within a building is required together with unobstructed outside walls the longitudinal frames have been designed to resist seismic forces as in buildings 4 and 6.

Floor slabs of reinforced concrete have in all cases been used as horizontal disphragms to transfer loads to the vertical elements resisting earthquake loads.

All the buildings are of reinforced concrete as this has proved to be the cheapest construction material for multistorey work and uses comparatively small quantities of steel which has to be imported.

All these buildings have been designed to withstand horizontel forces applied at each floor level equal to 10 per cent of the sum of all dead loads plus the estimated actual live load. In addition most of the buildings were checked to ensure that they could resist horizontal forces of 15 per cent of vertical loads at the top of the building reducing linearly to zero

Table I

	Building	*Location*	*Structures*	*Foundation*	*Soil*	*U.C.C.* lb./sq.ft.	*Found. Pressure D + L.L.* lb./sq.ft.	*Max. Pressure due to E.Q.* lb./sq.ft.	*Overall Height* ft.	*Gross Floor Area* Sq.ft.
1.	Departmental Office Building	Auckland	External & Internal Shear Walls & d & 1.1. frames	Caissons & Damping raft	Waitemata Beds & Clay	10,000 to 40,000 2,000 to 4,000	On Caissons 10,000	On Caissons 23,000	112	192,000
2.	Flats	Auckland	Shear Walls	Raft	Waitemata Beds	10,000	2,500	4,000	110	70,000
3.	Flats	Wellington	Shear Walls	Grouted Cast In situ Piles	Piled to Greywacke	—	Pile load 30 tons	Pile load 45 tons	100	70,000
4.	University Dental School	Dunedin	External Transverse Shear Walls Deep membered frame longitudinally plus d & 1.1. frame	Designed for footing built on cast in situ piles	Estuarine deposits over conglomerate	—	Pile load 45 tons	Pile load 60 tons	60	82,000
5.	Departmental Office Building, Bowen St	Wellington	Internal Shear Walls plus d & 1.1. frames	Raft	Preconsolidated silts with lenses of clays sands and gravels	1,500 to 10,000 average 6,000	3,600	6,500	164	220,000
6.	Printing Works	Wellington	Shear Walls Transversely Frames longitudinally	Separate Footings		C = similar $\Phi = 0$ to 35°	6,000	8,000	114	174,000
7.	Dormitory & Store	Auckland	External Shear Walls Internal d & 1.1. frames	Piles	Piled through reclamation to Waitemata beds	10,000 to 40,000	Pile load 35 tons	Pile load 50 tons	48	26,000
8.	University Teaching Laboratory	Christchruch	External and internal shear walls	Strip footings	Alluvial Silts & gravels	—	10,000	16,000	110	97,000
9.	Departmental Office Building Aitken St.	Wellington	Internal Core with regular openings external d & 1.1. frames	Raft	See 5 & 6	See 5 & 6	4,000	5,600	250	168,000

at ground level. These seismic loads are specified in the New Zealand Building Code but when applying the loads allowable stresses in steel and concrete are increased by 33 $\frac{1}{3}$ per cent. In addition the New Zealand Building Code N.Z.S.S. 95 Part III requires that foundations shall be tied in two directions at right angles with members which are designed to carry both the moments induced by the supported member and the compressive or tensile forces equal to the load in the most heavily loaded base times the appropriate seismic factor.

There is no specific provision in the Code for any adjustment of the seismic coefficient to suit ground conditions. For a national code there are obvious advantages in maintaining uniformity. Within the Ministry of Works each building is treated on its merits and a seismic coefficient higher than normal is allotted to a building if it possesses abnormal characteristics either in foundation materials or in form of construction. In arriving at a coefficient the data available from overseas, as outlined below, is an important guide.

The problem has been overcome on all major buildings by purposely avoiding the use of shallow foundations on poor materials. As long as excavation costs remain low this practice is likely to continue.

For good foundation materials, such as dense well graded gravels and sands and preconsolidated clays and silts, allowable stresses in soils due to seismic loads are increased up to twice the value allowed for normal loads, see Table No. 1.

Building foundations

Building 1 has caissons designed to varying diameters to give a consistent foundation pressure under dead and live load of 10,000 pounds per sq. ft. Under the design horizontal forces this pressure increases to a maximum of 23,000. This increase is very large and had the caissons been designed with an increased size of footing for the higher loads then it is likely that differential settlement would have occurred under normal loading. The building may possibly complete its useful life without being subjected to the design seismic forces. To reduce the seismic loads on the caissons and also to give damping to transverse movement the ground slab has been designed to raft, allowing up to yield point stresses in the reinforcing steel. This is not a precise design but it is contended that it is no less precise than the original assumptions. Special construction methods were specified to ensure support under the ground slab.

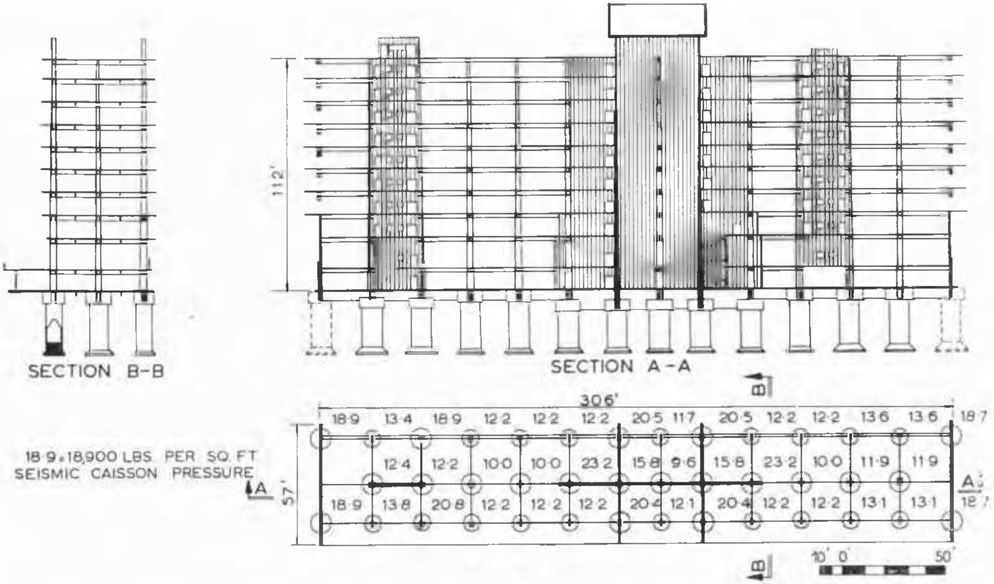
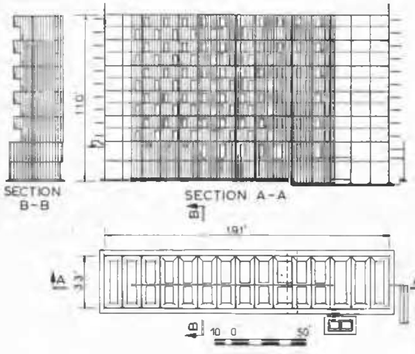


Fig. 1 Departmental Office Building, Auckland.
Bâtiment administratif départemental, à Auckland.



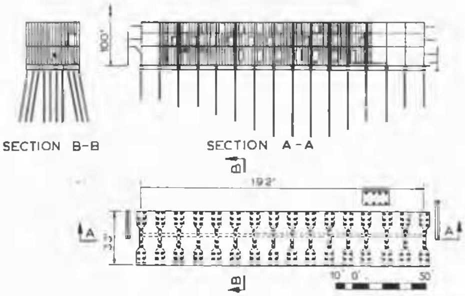


Fig. 3 Flats, Wellington.
Appartements à Wellington.

Fig. 2 Flats, Auckland.
Appartements à Auckland.

Building 5 is the logical development from No. 1. It is an improvement as it avoids eccentricity of stiffness. The ground slab is used as a raft. It is one of the tallest buildings in New Zealand and to obtain overall stability the shear walls have been widened at the base thus mobilising the vertical loads of the outside frames.

The average pressure on the raft under dead and live loads is 3,600 pounds per square foot which increases to 6,500 under the seismic design load. Rebound of the soil was not anticipated due to the heavy preconsolidation but it was found in practice that the operation of heavy earthmoving equipment in wet weather worked up the silts and clays to a high moisture content and over excavation and backfill was needed over large areas.

Building 9 is a further development of this type with a gross dead and live load weight of 40,000,000 pounds and a raft area of 10,000 square feet. When subjected to the horizontal design force the maximum pressure increases to 5,600 pounds per sq. ft. and there is a factor of safety against overturning of 3. This compares with the minimum allowed by the New Zealand Code of 1·5. It is considered in a building of this type where all the vertical load has been mobilised against overturning that a high factor of safety is necessary. Other buildings described have lower safety factors but in those cases additional righting loads can be brought into play if excessive deflections occur.

Building 8, which developed from the work done on Building 7, is an example of the use of external walls to resist seismic forces. With ground water level only 5 feet below the surface the most important function of the site investigations was to check the relative densities of the materials. For multi-

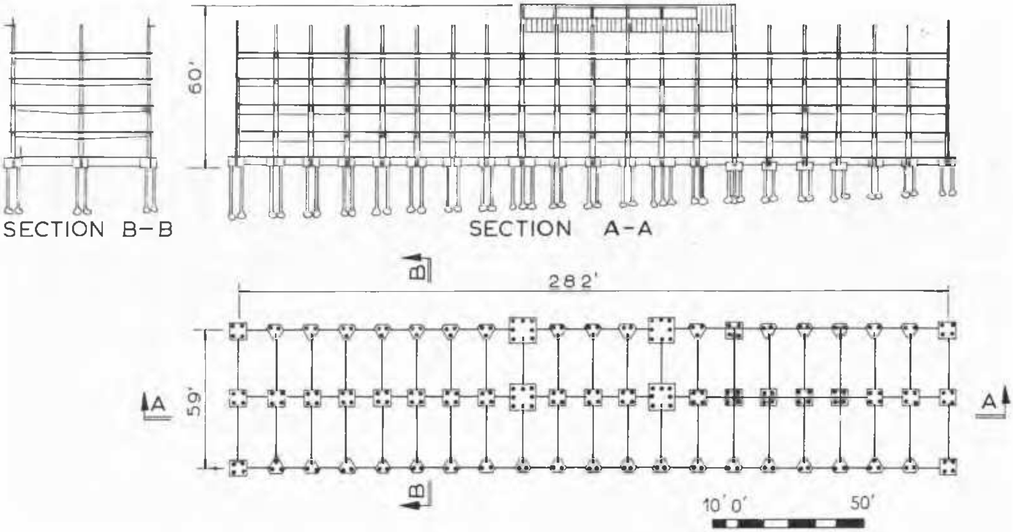


Fig. 4 University Dental School, Dunedin.
Ecole dentaire de l'Université de Dunedin.

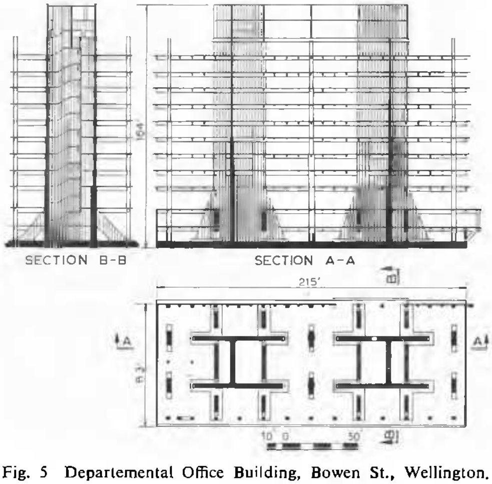


Fig. 5 Departemental Office Building, Bowen St., Wellington.
Bâtiment administratif départemental, rue Bowen, Wellington.

storey buildings in seismic areas an arbitrary minimum figure for relative densities of foundation materials has been made $R_D = 0{\cdot}85$. Had unsatisfactory materials been encountered on this site it is likely that deep foundations, most probably piles would have been used. Compaction by vibration is being investigated at present but the presence of gravel on this site would have precluded its use.

Building 6 uses the end walls to resist lateral horizontal forces but as this is not a particularly tall building the frames are used to provide longitudinal stability. In this case internal longitudinal walls would have interfered with free flow of printing materials and with machines and conveyor lines.

Buildings Nos. 2 and 3 have similar superstructures and were initially both designed to be founded on piles. The Auckland building was redesigned to have a raft foundation to save construction time. The raft is founded on the Waitemata Beds as the surface clays are highly compressible. The unconfined compression strengths of the clays varied from 4,000 pounds per sq. ft. at the surface to 2,000 at 15 to 25 feet deep. The excavations left net increases of pressure on the foundation of only 300 to 1,000 pounds per sq. ft. It is interesting to note that the Auckland building took 9 months less to build than that in Wellington founded on cast in situ piles.

Building codes

Building Codes show great variation from one country to another in the whole approach to aseismic design. The allowances to be made to provide for the foundation conditions encountered are probably the most variable factor of all. In the N.Z. Code there is no provision in the the seismic coefficient for differing ground condititions, the 10 per cent (or 15 per cent to 0) referring to all types of ground.

In Japan the regulations state the seismic coefficient to be applied to the building depending on both the materials of construction and on the foundation material. For timber buildings a coefficient from 12 per cent to 30 per cent is used, for steel frame 12 per cent to 20 per cent and for reinforced concrete 16 per cent to 20 per cent. The smaller coefficient applies to rock, hard sandy gravel classified as Tertiary or older whilst the larger coefficient applies to sandy gravel, hard clay, and loam, classified as diluvium, except in the case of timber buildings where the higher value applies to estuarine deposits or reclamations.

It must be remembered when comparing coefficients that the Japanese allow very high working stresses in seismic design namely 34,200 p.s.i. for structural steel in tension and 2,000 p.s.i. for concrete (3,000 p.s.i. crushing strength) in compress-

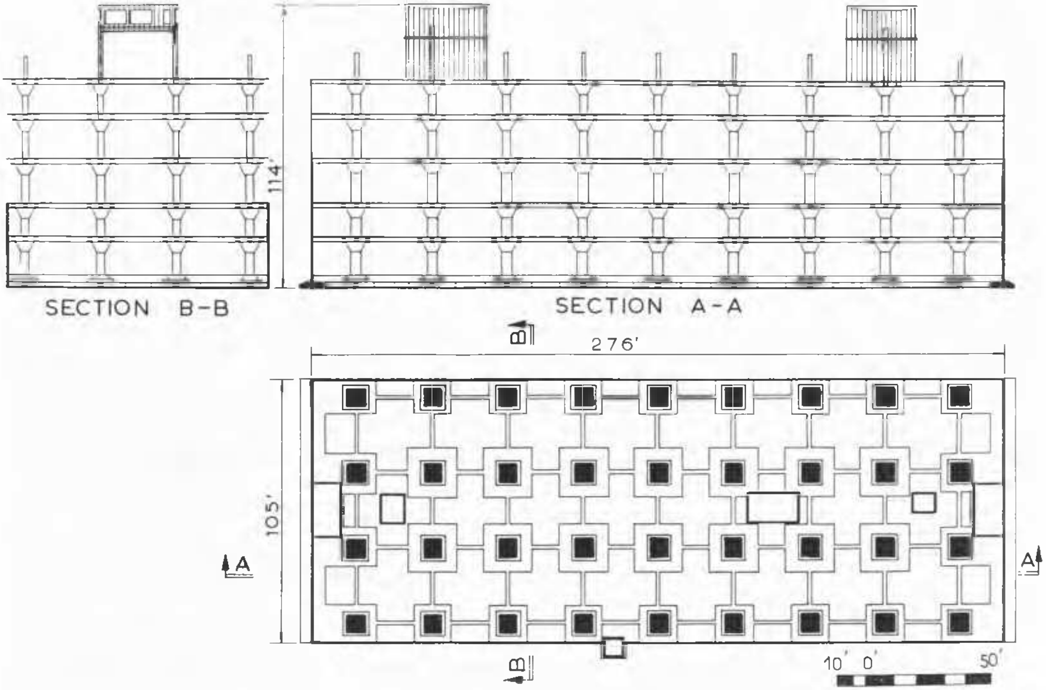


Fig. 6 Printing Works, Wellington.
Ateliers d'impression, à Wellington.

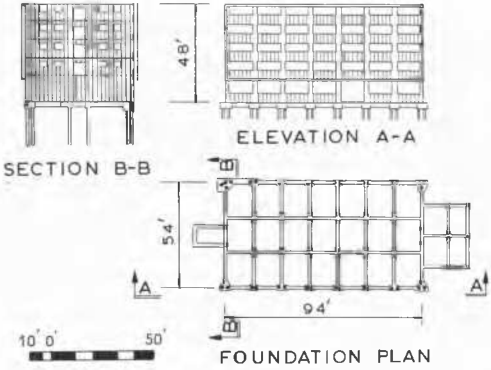


Fig. 7 Dormitory and store, Auckland.
Bâtiment à usage de dortoir et magasin à Auckland.

ion. Under similar circumstances the allowable stresses in New Zealand are 24,000 and 1,200 p.s.i.

In Chile lower coefficients are allowed for semi-rigid buildings (Period 0·4 to 0·75 secs.) on rock and compact soils than for rigid buildings (Period < 0·4 secs.) whilst for loose materials the rigid buildings are allowed a lower coefficient. The total range is from 5 per cent to 15 per cent.

In Quetta, India, foundation pressures are limited to one ton per square foot.

Various State regulations on the West Coast of the U.S.A. have coefficients related to safe bearing pressures in the order of 6 per cent for 4 tons per sq. ft. to 10 per cent for 2 tons per sq. ft.

The recommendations published by the French Ministry of Public Works after the 1954 earthquake in Algeria gave factors to be applied to the seismic coefficients depending on foundation type and soil type as follows :

Medium soil, superficial foundations	Factor 1·25
Sound rock, deep foundations	0·75
Sound rock, superficial foundations	0·94
Soft saturated soils, deep foundations	1·25
Soft saturated soils, superficial foundations	1·56

These recommendations also covered allowable stresses in soils subjected to seismic loads, which are worthy of attention, as follows :

Sound rocks : 3 times the allowed pressure under normal conditions.

Saturated soils : The same as under normal conditions.

Other soils : Twice the normal pressures.

Soil behaviour

The conclusions to be drawn from research work (Murphy, 1960, Eastwood, 1953; Okamoto, 1956) are that the vibration of loads has little effect on clays and most dry silts at the

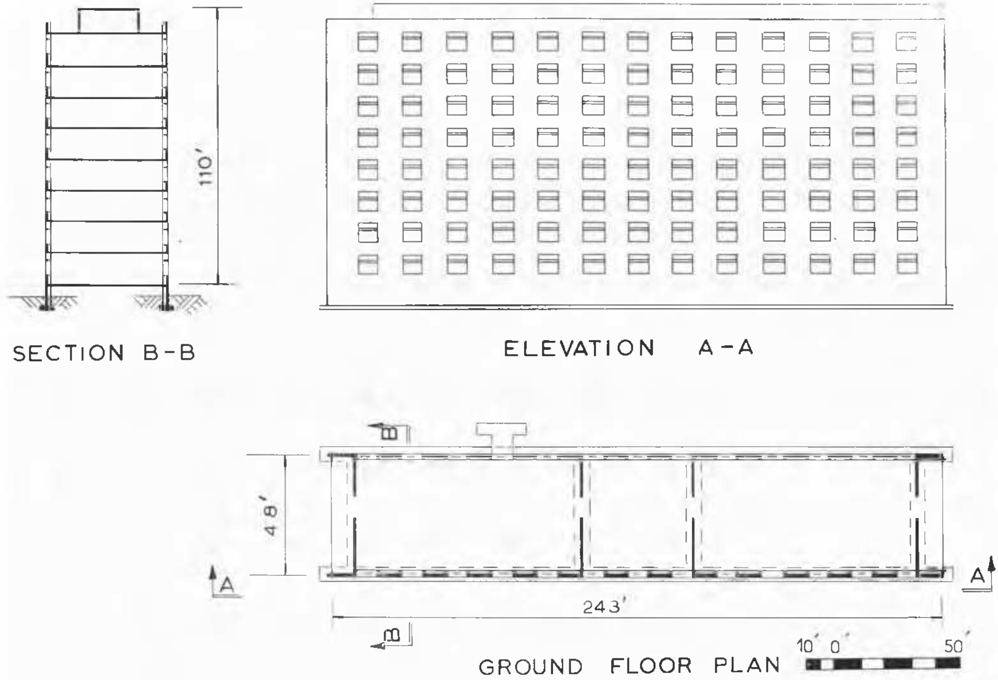


Fig. 8 University teaching Laboratory, Christchurch.
Laboratoire d'enseignement de l'Université de Christchurch.

periods experienced in earthquakes whilst sands and saturated silts are extremely sensitive. There appears to be, in addition, a critical acceleration between 30 per cent and 50 per cent g. above which sand loses its strength rapidly.

This weakness underlines the importance of the measurement of in-situ densities of sands and silts. The measurement is complicated in many New Zealand districts by the presence of iron sands in thin strata.

A separate influence of soft materials particularly when found to great depths is the increase they appear to give to actual earthquake forces. Opinions (Housner in U.S.A. Kanai and others in Japan) are sharply divided on the subject but the Japanese evidence has the advantage of being based on more data. C. Martin Duke has published much useful information on this and other related subjects.

Building behaviour

There have been four earthquakes which have caused major damage in built-up areas of New Zealand over the past 40 years. In no case has structural damage been reported in buildings which have been specifically designed and detailed to resist earthquakes upon the lines outlined in this paper.

The Murchison earthquake, in June 1929, damaged many buildings in Nelson city. The damage was greatest in the business area of the town which lies on alluvium. However, the Nelson College which is higher on the Tertiary slopes was badly damaged. This damage could be accounted for by the lack of crosswalls in this heavy masonry building. A school building at the foot of the hills also of masonry construction but well tied with cross walls survived with only slight cracking.

Much of the damage to other buildings could be attributed to the entire absence of ties at foundation level.

The Hawkes Bay earthquake in February 1931 almost completely destroyed the business areas of the towns of Napier and Hastings except for reinforced concrete buildings and particularly well designed masonry buildings. In Napier city and surroundings masonry buildings on Tertiary limestone hills were also destroyed. The two town centres were built on very recent alluvial deposits. Severe damage was caused to earth fills in road and railway embankments and in some cases the slumping of fills damaged bridge abutments. The absence of foundation ties again was a contributing factor to the damage of many buildings.

Two earthquakes in 1942 in the Wellington province caused damage to buildings in both the City of Wellington and to smaller townships to the north. These earthquakes affected a wide variety of foundation materials. In Wellington City buildings founded on the preconsolidated clays and silts had less damage than those on the loose gravels and reclamation of the foreshore. Very severe damage was caused to even single storey buildings in the Otaki area founded on sand dunes (since discovered to have very low relative density) and on soft silts.

The most comprehensive quantitative work in the field of building behaviour has been done in Japan. H. Kawasumi showed that in the Kanto earthquake of 1923 damage to wooden buildings increased as the depth of alluvium on which they were founded increased. K. Kanai, however, when

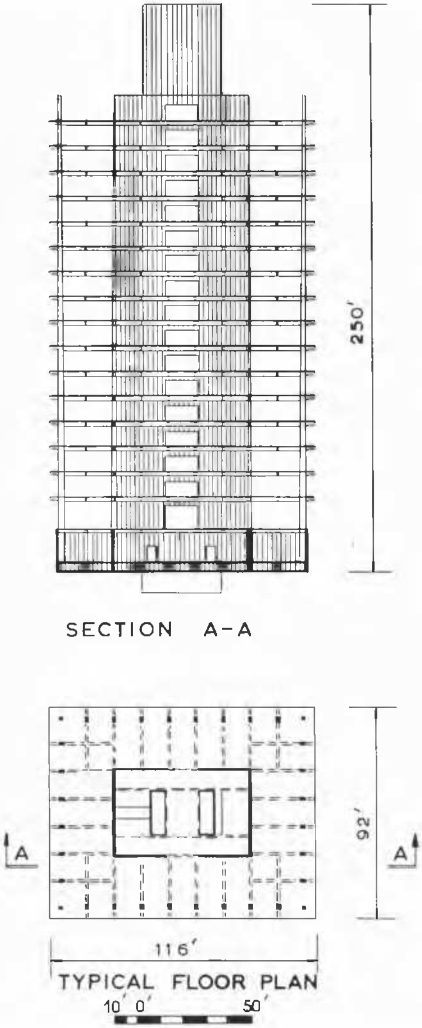


Fig. 9 Departemental Office Building Wellington Aitken St.
Edifice administratif départemental, rue Aitken, à Wellington.

examining the effects of the same earthquake on brick and concrete buildings found the greatest damage on shallow depths of alluvium. G. Kitazawa studying damage to structure only, found increase in damage with increase in ground softness.

In the Mexico earthquake of 1957 greater damage was caused to flexible multi-storey buildings in Mexico City 200 miles from the epicentre than to similar buildings in Acapulco only 60 miles from the epicentre. The buildings in Mexico City were founded on very deep soft alluvium and those in Acapulco on rock or well graded sands.

Similarly in the Quetta earthquake of 1955 buildings similar in construction showed less damage though closer to the epicentre if founded on good foundation material.

Only the very general conclusion can be drawn from these records that weak foundation materials increase risk of earthquake damage, except that, very heavy rigid buildings appear to suffer much damage when founded on rock.

Conclusions

(1) There are good grounds for employing increased seismic coefficients for buildings founded on weak compressible soils. The Japanese regulations are the most comprehensive in this field but an adjustment for heavy buildings on rigid foundations could well be included.

(2) A lower factor of safety from damage due to settlement or complete failure seems justified, when increased loads are due solely to seismic forces.

(3) Seismic loads cannot be the governing factor in determining foundation sizes as the emphasis must in most cases be placed on avoiding differential settlement under dead and live vertical loadings.

(4) Sands and silts of low relative densities particularly when accompanied by high ground water levels must either be avoided or compacted in seismic areas.

(5) The conclusion that the design of both foundations and superstructures to resist seismic forces will remain arbitrary for some considerable time appears justified, in view of the infrequency of full scale tests. None of the buildings described, for example, have yet been tested to design loads and undoubtedly their occupants will be quite happy for that state of affairs to continue indefinitely.

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