11 WCEE

Copyright © 1996 Elsevier Science Ltd
Paper No. 499. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

BASE ISOLATION TO PROTECT NEW ZEALAND'S HERITAGE

P R Boardman and T E Kelly

Holmes Consulting Group, PO Box 99-450, Newmarket

Auckland, New Zealand

ABSTRACT

The Museum of New Zealand, Te Papa Tongarewa, is the repository of national treasures and cultural icons essential to the preservation of the country's heritage. The location selected for a monumental building on the Wellington waterfront to preserve and display the collection presented particular problems for the structural engineers - although the city is in New Zealand's most active seismic region and the site was on reclaimed land, the building was to be designed for a 150 year design life, meeting stringent criteria for the prevention of damage and have a structural system which conformed to the functional requirements of the building.

Design studies showed the benefits of base isolation to reduce floor accelerations and damage to contents. The first cost of a base isolated structure was slightly higher than for a fixed base structure, \$15.1m structural cost versus \$14.5m.

The combination of dynamic consolidation of the site and installation of a base isolation system comprised on lead-rubber bearings and Teflon sliding bearings was demonstrated to be a cost effective solution to reconciling functional and structural performance conflicts in the design and construction of a building to house irreplaceable contents.

KEYWORDS

Seismic Design, Base Isolation, Museums & Contents, Dynamic Consolidation, Cost Effective

MUSEUM OF NEW ZEALAND

Introduction

The Museum of New Zealand, Te Papa Tongarewa, is a repository of national treasures which are presently housed in several structures in Wellington. A new building is being constructed on the Wellington waterfront to combine the functions of exhibition, storage and research.

The building is to be monumental in nature with a total floor area of 35,000 square metres distributed over five floor levels. The design team headed by Jasmax Architects was selected in 1990 after an international competition. Design development is completed and final design and production of working drawings is in progress. Construction is scheduled to finish in 1997.

This paper describes the feasibility study performed to assess the benefits of base isolation and design studies undertaken as part of a value engineering study to document the cost impact of various structural schemes. A decision to proceed with isolation was made at the conclusion of these studies. This paper summarises the design of the structure and the isolation system and the three-dimensional nonlinear analyses performed to evaluate the building performance.

Museum of New Zealand, Te Papa Tongarewa

The building site on the Wellington waterfront is on reclaimed land which has been infilled over the last 40 years using high quality fill material which is uncompacted. Approximately 12m of this fill material overlays up to 100m of dense sand and gravel. A number of alternate deep and shallow foundation schemes were investigated of which the most cost effective was found to be dynamic consolidation of the site and the use of pad footings without piles. A pilot study using dynamic consolidation (dropping a weight of 25 tonnes a height of 25 min a fine grid pattern) has been performed over a portion of the site and has demonstrated its effectiveness to a depth of 12m. The level of the site reduces approximately a metre as a result of the consolidation.

The new building approximates a triangle in plan with maximum dimensions of 120m x 190m and a height of 23m. Figure 1 shows the layout of the building at the isolation level. Total building costs is estimated to be $NZ130 million.

A number of preliminary value engineering studies by the entire design team investigated alternatives of reinforced concrete and structural steel and also a number of floor span configurations. The optimum system selected is a reinforced concrete structure based on a rectangular grid of 17.4m x 8.7m with precast floor units. Ductile frames were selected in the direction of the 8.7m grids and shear walls in five locations in the 17.4 m span direction. The frames are formed of pairs of columns/girders spaced 2.1m apart. The double frame system has the effect of reducing the span of the floor units from 17.4m to 15.3m and also providing a system of "tunnels" for the building services.

Seismic Design Criteria

The site is in the most seismically active region of New Zealand (Zone A) and specific earthquake performance requirements were set as part of the design brief, in particular :

1. Probability of significant damage less than 50% in 150 years, which corresponds to a 250 year return period.

2. Probability of collapse less than 7% in 150 years, corresponding to a 2000 year return period.

For the reinforced concrete structural system, the onset of "significant damage" was defined as (1) displacement ductility less than 2 and (2) concrete strains less than 0.004, which correspond to plastic rotations of approximately 0.007 radians. The limit beyond which collapse could occur was set at a strain of 0.010 a plastic rotation of 0.020 radians. Analysis procedures were required to be such that these values could be quantified.

Site specific earthquake acceleration time histories and response spectra were generated for each of the return period using the SHAKE computer program to obtain surface records. Source time histories were based on 1.8 x El Centro 1940, 0.7 x Tabas 1978 and 1.3 x Llolleo, 1986. An additional record was generated by frequency scaling the El Centro 1940 record to be compatible with the smoothed surface spectrum. Figure 2 shoes the 500 year spectrum together with the 1940 El Centro N-S component before and after frequency scaling. The 250 year and 2000 year return period spectra were obtained by a linear scaling of the 500 year spectrum by factors of 0.8 and 1.3 respectively.

The 250 year spectrum is about 50% higher than would be required by the loadings code for the Wellington region. In addition, the damage criteria restrict the ductility factor to 2 rather than the 6 permitted by the code for ductile concrete frames. The net result of this is that elastic design forces for the building are 4.5 times higher than would be required for a building designed to the code. This level of design load and the desire to restrict contents damage formed the basis for the decision to investigate a base-isolated structure for the museum.

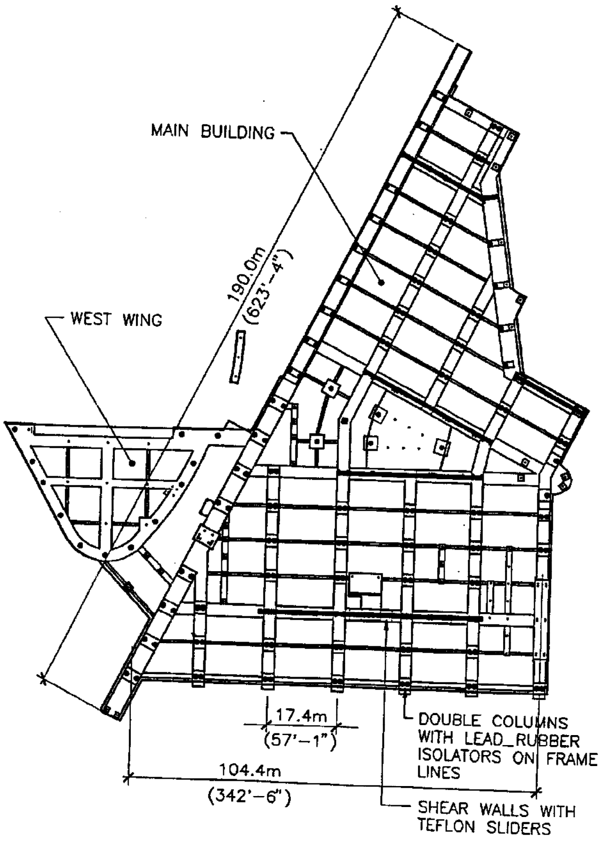

Fig. 1. Building Layout

Feasibility Study

Seismic isolation was included in the initial concept development of the building but, as part of the value engineering requirements of the project, its cost effectiveness was to be justified at each stage of design. A two stage feasibility study was performed, the first investigating global response parameters (base shear and floor accelerations) and the second evaluating and costing various frame and shear wall designs (drifts and ductilities).

The method used for the initial evaluation was based on a procedure developed by Ferrito [1] where the cost of damage to the structure and contents is estimated as a fraction of the initial cost. Design base shear levels of 0.2 g and 0.5 g were assumed for both a fixed and isolated building configuration. Maximum drifts and floor accelerations were estimated for each level of design and the cost of structural damage and damage to components assessed for each option using Ferrito's tables. Bar charts were produced (for example, Figure 3 for an 0.5g design level) based on an assumed total building cost of $50 m and contents value of $200 m. The procedure was approximate but did enable some conclusions to be drawn :

1. Total damage costs are 3 to 8 times higher for a fixed base building than for an isolated building, the actual factor depending on the design base shear level and magnitude of earthquake.

2. For the fixed based building damage costs actually increase if the design base shear level is increased even though costs of structural damage are reduced. This is because of the high value of the contents which are damaged by floor accelerations. Accelerations increase with increasing design level.

3. Even for an isolated building significant contents damage could occur at the 250 year earthquake level assuming a threshold of damage of 0.08g (as in the Ferrito study).

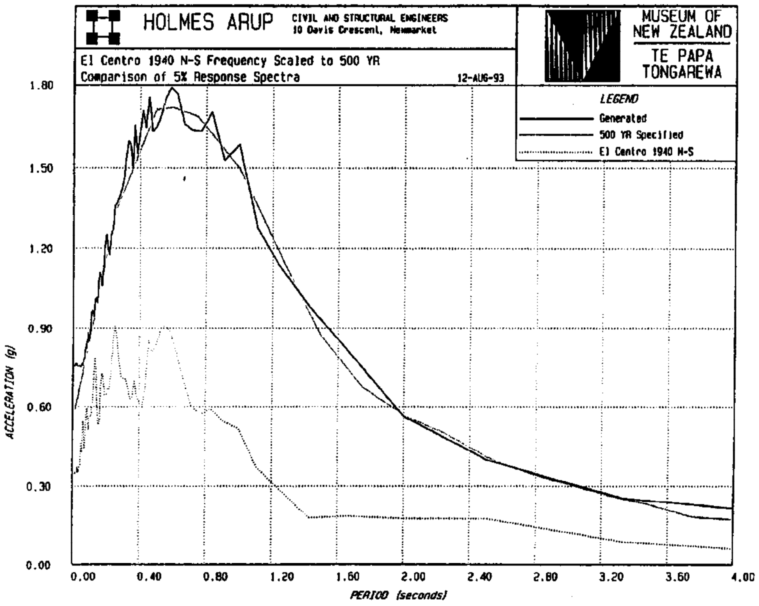

Fig. 2. Site Surface Response Spectrum

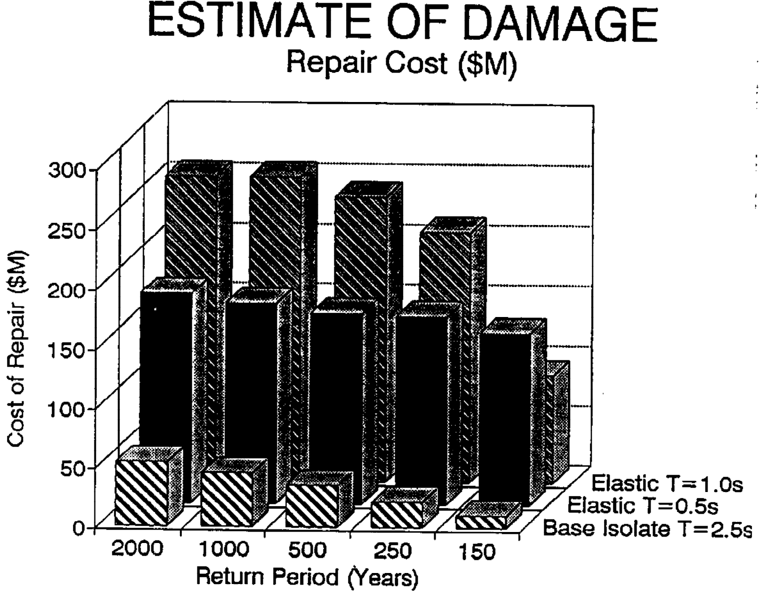

Fig. 3. Damage Costs From Feasibility Study

In the second phase of the feasibility study representative frames and shear walls were designed for base shear levels corresponding to varying levels of ductility at the 250 year level, from fully elastic to fully ductile. A time history analysis using the DRAIN-2D2 program was then used to compute the response at the 250 year and 2000 year return period earthquake for each design. Each design was evaluated for acceptability in terms of the criteria limits on damage and for each design the quantity surveyors for the project estimated the structural construction cost.

From a structural performance perspective both the fixed base and isolated schemes were able to be designed to achieve the criteria objectives limiting damage at the 250 year level and avoiding collapse for the 2000 year earthquake. This required that the frames be designed for a minimum of 50% of the 250 year elastic forces and the walls and coupling beams for 100% of the 250 year elastic forces. The fixed base configuration required 8 shear walls versus 5 shear walls for the isolated design and also required larger column and girder sections. The effect of these increases in the structural system sizes was to counteract the cost of the isolation system so that the two configurations produced similar structural costs, $14.5 million for the fixed base building and $15.1 million for the isolated building. Extra costs to accommodate the larger drifts in the fixed base building were not quantified.

The design options had demonstrated approximately equal costs for the two systems but of more importance for a building of this function is the cost of non-structural damage (related to drift and floor accelerations) and especially contents damage (a function of floor accelerations). As Table 1 shows, the fixed base options produced drifts and accelerations several times as high as the isolated alternative. These results lead to a decision to proceed with the isolation system design.

Table 1. Structural Drifts and Accelerations

	Maximum Floor Acceleration		Maximum Storey Drift	
	Fixed	Isolated	Fixed	Isolated
FRAMES				
250 Year	0.81	0.33	0.6%	0.2%
2000 Year	1.14	0.48	1.8%	0.7%
WALLS				
250 Year	1.02	0.27	0.5%	0.1%
2000 Year	1.69	0.38	0.8%	0.6%

Isolation System Design

As part of the feasibility studies varying isolation system parameters were studied but specific hardware was not designed. It was assumed that the system would contain the two essential elements of a practical isolation system in a high seismic zone, flexibility and added damping. Both hysteretic and viscous forms of damping were evaluated. It was decided that devices to provide hysteretic damping were more readily available than viscous dampers and so the design was based on hysteretic damping. After evaluating a number of systems, elastomeric bearings wit lead cores to provide hysteretic damping were chosen. These bearings were not suitable for the wall locations where high compression and tension forces occurred. At these locations PTFE (Teflon) sliding bearings were used, the bearings uplifting when earthquake induced axial loads exceeded the gravity load.

Architectural and services restrictions limited the maximum seismic gap around the building to 500 mm and so the isolation system design was required to produce displacements less than 500 mm at the 2000 year earthquake. This formed an upper bound on the flexibility of the isolation system.

The design of the lead-rubber bearings was based on procedures developed by Dynamic Isolation Systems, Inc [2]. Different isolator location configurations were investigated and it was found that a single, large isolator at each column location was more economical than multiple smaller isolators because of the large displacements. The isolators as designed have a maximum size of 950 mm diameter x 300 mm height.

Evaluation of Structural Performance

The final configuration of the structure and isolation system produced a very complex lateral load resisting system. To evaluate the performance a three- dimensional model of the structure and isolation system was developed using the ANSR-II computer program [3].

The computer model of the building was developed in successively more complex stages with each step forming a check on the overall response produced by the succeeding step. Initial studies on a single degree-of-freedom model were extended to planar models of the frames and walls and then to a three-dimensional model with an elastic superstructure. The final model was a fully yielding model which reflected all the elements of the building :

1. Flexural bi-linear yielding elements to model the frame girders and columns and the shear wall and coupling beams.

2. Special purpose gap-friction elements to model the Teflon bearings. The friction force for these elements was a function of the vertical pressure and velocity at each location at each time step of the analysis.

3. Lead-rubber bearings modelled as two components, a linear elastic element representing the elastomer and an elastic perfectly plastic element to represent the lead core.

4. Horizontal movement buffers at the isolation level which engaged when displacements exceeded 500 mm.

5. A rigid diaphragm at the North and South portions of the main building linked by truss elements to model the connection stiffness at the movement joints.

6. A West Wing "stick" model mounted on the same isolation diaphragm as the Main Building but separated from it at upper levels.

Results of Ansr-II Analyses

The ANSR-II model was used for a basic set of 16 analyses - 4 pairs of earthquake records, 2 orientations per record and 2 return period for each orientation. For each analysis the two horizontal components of motions were applied simultaneously. The global results from these analyses are summarised in Table 2 which lists the maximum values from the two orientations. Figure 4 shows the displacement time history of the isolation system and the structure for the El Centro SHAKE record. Figure 5 is an orbital plot of the total force in the Teflor elements for the same record. The total force tends to be within a circular upper bound formed by the maximum coefficient of friction of 0.12 at high velocities and low pressures.

	Earthquake 1 El Centro SYNTH		***Earthquake 2 El Centro SHAKE***		***Earthquake 3 Tabas SHAKE***		***Earthquake 4 Llolleo SHAKE***	
	X	***Z***	***X***	***Z***	***X***	***Z***	***X***	***Z***
250 YEAR EVENT								
Frame Displacement (mm)	104	122	83	71	93	90	96	126
Wall Displacement (mm)	51	45	38	40	47	36	48	48
Isolator Vector Displacement (mm)	247	224	199	209	246	258	205	241
PTFE Pad								
Uplift (mm)	20	16	10	17	15	21	11	25
Compression (KN)	34390	32180	27330	33280	31260	36440	28300	35920
2000 YEAR EVENT								
Frame Displacement (mm)	109	270	192	132	199	162	177	154
Wall Displacement (mm)	118	90	84	60	96	64	84	69
Isolator Vector Displacement (mm)	484	477	452	443	477	516	415	421
PTFE Pad								
Uplift (mm)	79	48	54	55	41	36	22	56
Compression (KN)	44820	43440	44630	41880	41990	40350	33820	41980

Fig. 4. Analysis Results

Conclusion

A series of feasibility and design studies performed for the Museum of New Zealand, Te Papa Tongarewa, have demonstrated that a seismic isolation system can be installed for almost the same first cost as a conventional, fixed base structural system.

To obtain approximately similar levels of structural damage, the conventional structure requires larger columns and beams and also a larger number of shear walls compared to the isolated structure.

The consequences of designing a fixed base structure for very high levels of earthquake load are to increase the floor accelerations far above those of the seismically isolated scheme and so increase the potential for damage to non-structural components and contents. For a building such as a museum, the values of the contents may be many times the value of the structure. When this is taken into account, the total damage costs in a major earthquake in a fixed base building can be from 3 to 8 times those of an isolated building. This was the deciding factor in the selection of an isolated configuration for the building.

The isolation system selected was a combination of elastomeric bearings with lead cores and PTFE (Teflon) sliding bearings. The elastomeric bearings are used at column locations and the Teflon bearings at shear walls where high overturning forces occur. A nonlinear analysis model was used to quantify the isolator forces and displacements and the ductility demands in the concrete superstructure. Some adjustments to the column reinforcing were made as a result of these analyses.

The design and evaluation of earthquake response has demonstrated that, even with seismic isolation, the maximum earthquake motions to be expected in the high seismic Wellington region will cause relatively high in-structure accelerations. These will be of a level which could cause damage to contents and services unless mitigation measures are taken. Consideration of earthquake effects will need to be included in the initial design of all aspects of the building and also of the placement and fixing of contents during the operation of the building.

REFERENCES

Ferrito, J., (1984). Economics of Seismic Design for New Buildings, *ASCE Journal of Structural Engineering, December.*

Dynamic Isolation Systems, Inc., (1990). *Seismic Isolation of Buildings, November.*

Mondkar, D.P. and Powell, G.H., (1979). ANSR II Analysis of Nonlinear Structural Response User's Manual, *EERC 79/17, University of California Berkeley, July.*

Habibullah, A., (1986). ETABS Users Manual, *Computers and Structures, Inc.*

Mokham A,m Constantinou, M.C. and Reinhorn, A.M., (1988). Teflon Bearings in Aseismic Base Isolation : Experimental Studies and Mathematical Modelling. *NCEER-88-0038, State University of New York, December.*

Davidson, B.J. and Smith, M.D. (1992), Size Effects of PTFE Bearings for Aseismic Base Isolation, *Auckland, New Zealand, November.*