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The 1992 Roermond earthquake, the Netherlands: earthquake engineering

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Abstract

An overview of the structural damage resulting from the April 13, 1992 Roermond earthquake is presented. Rather than addressing the need of code requirements to enhance the structural integrity of buildings in low-intensity seismic zones such as the Roermond region, the paper addresses the effects of the basic architectural form of buildings which can dramatically affect the seismic resistance of buildings and adversely affect the possibility of structural survival. Particularly in regions of low seismicity, considering the influence of zoning and architectural layout in building design will enhance the earthquake resistance of buildings far more than could be expected through the use of earthquake design code provisions. The paper discusses the effects of design 'errors' on the potential earthquake response of buildings and offers solutions to improve the seismic performance.

Introduction

Earthquake damage is not only a measure of the seismic intensity, but also, more importantly, an indicator of the appropriateness of the architectural design and structural layout as well as of the adequacy of design specifications and zoning provisions (in conjunction with geological site conditions). Such aspects are important not only for earthquakes in regions with high seismicity, but also for earthquakes in areas with low to moderate seismic risk.

Particularly, in areas with a low earthquake expectancy, where aseismic code provisions may be even nonexistent, a realistic, pragmatic interpretation of observed damage patterns can form the basis of design guidelines. In such areas, as for the Roermond region, it would certainly not be advisable to introduce complex seismic design code requirements for buildings and other structures. Experience has shown that implementing such provisions alone does not guarantee the structural integrity of buildings and other structures in the event of an earthquake.

Modern codes are aimed at designing effectively structures with an energy-absorbing capability (ductility) of certain elements. This design procedure permits absorption of the seismically induced energy through early yielding at certain locations without loss of structural resistance. For buildings in low-seismic regions, such a design approach would be too complex and uneconomical. Instead, it is far more important to design buildings according to certain pertinent guidelines covering design considerations such as: zoning (related to site-specific geological conditions), architectural planning (related to building layouts both in-plan and vertically), basic design principles (particularly in interface regions), quality control and on-site inspection.

Earthquake damage

The observed damage to commercial and residential structures in Roermond and in surrounding villages such as Herkenbosch (Netherlands) and Heinsberg (Germany) was typical for an earthquake with moment magnitude ($M_w = 5.4$) and a building inventory of almost exclusively masonry structures. The Roermond town centre is dominated by old masonry structures (some dating back to the 18th century and earlier). However, also more recent masonry houses, shops and

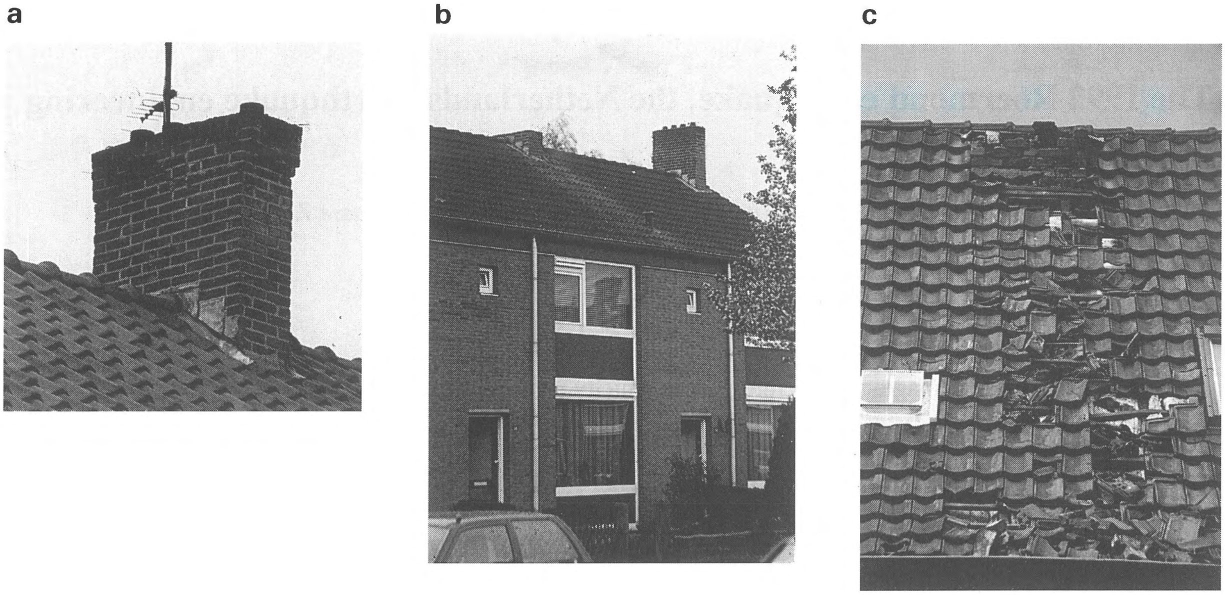

Fig. 1. Typical observed chimney damage due to the Roermond earthquake of April 13, 1992. a) torsional deformation, b) partial collapse, c) complete collapse.

churches form part of the central area. Outside the immediate centre, the building inventory covers modern housing, schools, apartment buildings and churches mostly built after the end of World War II. In general, only minor but widespread damage could be observed with a higher concentration occurring in the older area of town (EQE International 1992). The more modern commercial buildings and flats of either steel or reinforced concrete construction were apparently not adversely affected by the earthquake. However, the total of all damages has been estimated at over US $ 100 million (Berz 1994).

Specifically, as expected, the damage was restricted to failure of brick masonry chimneys and parapets (Fig. 1). Damage to chimneys typically showed horizontal cracking of the masonry above the roof level. In a number of cases a horizontal offset of the uppermost portion of the chimney could be observed. In only a very few cases the upper chimney portion had actually toppled over and damaged the tiled roofs. Other, less frequent damage could be observed as partial collapse of gable end-walls which had been inadequately tied to the wooden roof structure. In only a limited number of instances could significant diagonal shear cracking of exterior masonry walls be noted. Local damage to masonry due to pounding of immediately adjacent buildings could also be observed in a few cases.

A significant pattern of damage to churches, particularly older ones, could be identified. The damage to the 14th-century stone-masonry church at Herkenbosch was particularly serious and resulted in the structure to be condemned. Not only had the old stone-masonry portion been damaged extensively, also, the new brick-masonry belltower had experienced very serious damage. In fact, the presence of the steel scaffolding around the belltower appeared to have prevented total collapse of the upper tower portion. Also stone-masonry columns in the church interior had been damaged seriously. Other damage to churches was similar to that observed in several earthquakes in south-eastern Europe, namely, the outward movement of heavy exterior masonry walls and the consequential downward movement of masonry roof arches and vaults or roof timbers. Such motions resulted invariably not only in minor to serious cracking of walls but also, more pronounced, in the serious cracking of masonry roof arches and vaults. During the Roermond earthquake, in one instance, several single-layered brick-masonry vaults collapsed. The outward movement of heavy masonry walls could also be observed in at least one old farm building.

Geologically, a significant aspect of the Roermond earthquake has been the slope failures of low embankments along the Maas river to the northeast of Roermond and the evidence of sand boils near the river, indicating liquefaction (Alkema et al. 1994, Davenport et al. 1994, Maurenbrecher et al. 1994).

Considering the earthquake effect on industrial facilities, damage to structures and facilities was sporadic. Several chemical, petrochemical and power facilities were located along, or in the near vicinity of the Maas river. In one instance, the separation of two industrial buildings, one in steel framing with masonry in-fill walls and one constructed in reinforced concrete with also brick masonry walls, has been observed. Nonstructural damage of some PVC piping has been reported in a chemical processing plant south-southwest of Roermond, next to the river Maas. In several facilities around Roermond as well as at a vast petrochemical complex at Geleen, about 30 km south-south-west of Roermond, vibrations caused electrical safety switches or turbine-vibration monitoring instruments to be tripped causing a safety shut-down of pertinent equipment. Invariably, following inspection, full services could be reactivated within a matter of hours.

Earthquake engineering design

In the absence of pertinent earthquake design codes in low to moderate seismic regions, such as the Maas region, it would be more than adequate to have Regional and City Building Departments set simplified earthquake load design guidelines rather than requiring the use of specific aseismic design specifications as defined by international codes, such as Eurocode 8 (ENV 1998-1-1,2,3 1994). In general, the local and regional building inventory could be categorized in a limited number of structural systems, e.g. brick-masonry housing, reinforced concrete frames (with and without brick-masonry infill walls), reinforced concrete shear-wall buildings (with and without masonry walls) and steel-trussed and moment-resistant frames. Authorities could well stipulate for each building category the horizontal design loads (percentage of the structural weight) which the designer could use instead of following the provisions set forth in a pertinent earthquake design code. This would basically require that authorities define the categories and carry out, using for instance Eurocode 8 provisions, pre-analyses of common types of buildings in order to set up simple design guidelines based on type of system and common construction standards.

In addition to such simple design guidelines, a number of basic considerations have to be implemented if damage under future earthquakes is to be minimized. These considerations range from zoning provisions and architectural planning to quality control and inspection.

Zoning

Based on geological site conditions, zoning provisions are absolutely essential. The observed slope failures of the Maas embankments as well as the observed soil liquefaction in the flat lands along the Maas river, clearly illustrate the danger of building along or near the Maas, or for that matter in the flat lands along any major river in western Europe (e.g. Rhine), where such river passes through a seismic zone. The typically soft soil layers of clay and water-saturated sand are prone to be subjected to amplified ground shaking of long duration (several times the actual earthquake duration at the source). The conditions around Roermond are similar to the conditions near Liège where the Maas (Meuse) passes through a relatively narrow valley with high grounds on either side. Observations of damage from the 1983 Liège earthquake (Camelbeeck et al. 1985) showed a larger damage intensity in the low area as compared to the damage on the higher grounds. In fact, the influence of local subsoil conditions on structural damage has been observed dramatically worldwide in numerous recent earthquakes, namely: Thessaloniki in the 1978 Northern Greece earthquake, Budva in the 1979 Montenegro earthquake, Mexico City in the 1985 Mexico earthquake, Leninakan in the 1988 Armenian earthquake and San Francisco/Oakland in the 1989 Loma Prieta earthquake.

Admittedly, industrial facilities, including power plants, are often located along rivers or even on man-made landfills in the river flood areas. Although the site selection offers optimal access to river transportation and possibly needed cooling water, the earthquake damage potential is high even when such structures are well founded on deep piles. As illustrated by the post-earthquake observations along the Maas near Roermond, not only the potential of structural damage, but also damage to plant operations has to be considered in design. If an operator accepts this risk and damage does not endanger the population, such areas can be zoned for industrial use. However, housing in such areas should be prevented. Hence, it is advisable to exclude river front regions from zoning for residential or other high-occupancy construction (e.g. office buildings).

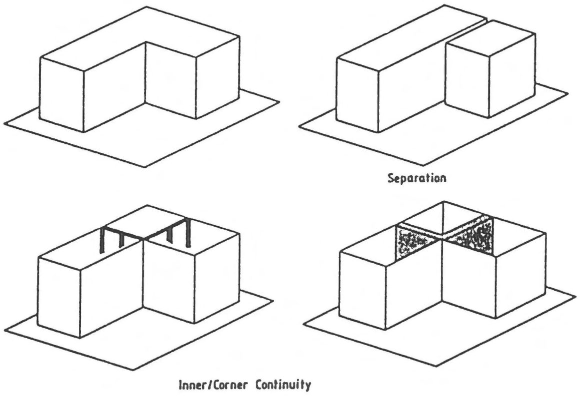

Fig. 2. Examples of asymmetrical buildings (L-shaped).

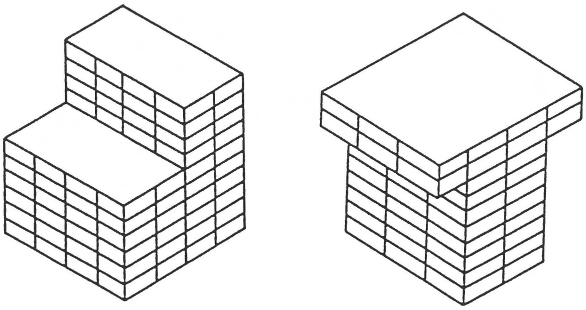

Fig. 3. Examples of irregular buildings (Vertical layout).

Building layout: horizontal and vertical

Horizontal layout

In general, whenever possible, the floor plan of buildings should be symmetrical in order to prevent structural distress under earthquake. Also, the lateral stiffness should be distributed such as to reduce torsional motion during an earthquake. Hence, guidelines should draw attention to the inherent dangers of buildings with L, H and T-shaped floor plans and stipulate the necessity to give special attention to the structural layout. At the inner corners, the orthogonal load transfer of incoming walls has to be accommodated by providing a structural system which permits a direct transfer of exterior wall forces into the interior of the structure (Fig. 2). The best solution would be a separation of the different portions of such buildings and leaving a sufficiently large distance between the several parts in order to prevent a pounding or hammering effect between adjacent portions under earthquake exposure.

An other area to be addressed in guidelines would reflect the fact that post-earthquake observations have shown repeatedly the inherent dangers associated with the design of hotels and hospitals. The functionality of such facilities often requires at the ground floor-level large open wall-free spaces for reception areas, restaurants and cafeterias as well as large to very large meeting rooms. In such facilities it is absolutely essential that the lateral load resistance at that level is assured through an adequate, properly balanced, layout of columns and walls. Failure to do so has had catastrophic consequences as numerous examples testify (e.g. Olive View hospital, San Fernando earthquake, USA, 1972; Budva hotel complex, Montenegro earthquake, Yugoslavia, 1979).

Vertical layout

In addition to considering the horizontal plan layout, equally important is the vertical layout of the building. Foremost in that respect is the absolute need that lateral-load-resisting elements such as walls and frame columns are continuous over the height of the building. Interrupting this continuity, even by an offset, can lead to serious damage or even collapse. Again, because of their functionality, hotels and hospitals may have typically such a 'built-in' structural deficiency. The upper floors, with an invariably very systematic layout of rooms, are structurally quite rigid. The combination of the upper, rigid, box-like system and the relatively weaker lateral load resistance at the open-spaced ground-floor level is potentially critical. This jump, vertically, in both stiffness and resistance, introduces a 'soft' first-floor storey which is often prone to collapse. In order to prevent such a response, it is absolutely essential that certain shear walls run continuously over the height of the entire building.

Also, buildings with vertical setbacks or cantilevering storeys (single or multiple floors), as shown in Fig. 3, are prone to serious damage under earthquake motion. In case of setbacks (e.g. penthouse) it is essential to assure the structural continuity of the setback portion, through columns or walls, over at least one, preferably more storeys immediately below the setback level. In case of cantilevering storeys, the lateral and vertical-load-resisting elements immediately below the cantilever portion need to be continued upward through that portion. Failure to introduce such structural measures may lead to serious structural damage (either beneath the setback level or in the cantilever storey, respectively).

System combinations

Another source of not only structural but also nonstructural damage may result when infilled brick-masonry walls or stiff infill panels are placed in a frame-type building for which the reinforced concrete or steel frame has been designed to resist the full lateral design load.

In principle, the addition of basically rigid brick-masonry walls or prefabricated concrete wall panels in a building with relatively flexible beam-column frames, increases the overall building stiffness and may seriously change the magnitude of the earthquake forces which the building experiences. Also, because of the added elements, the manner in which the structure resists the earthquake-induced loads may change significantly. In every earthquake, numerous cases have been observed whereby these changes have led not only to nonstructural damage of masonry walls or infill panels, but also to damage of structural elements which, in turn, led in many cases to the collapse of the building. In general, the architectural use of brick masonry in buildings designed as framed structures can lead to significant damage in future earthquakes.

For instance, placing masonry-walled corridors at every floor level of a framed building can have serious consequences. Because of the significantly larger in plane stiffness of the walls as compared to the frame, the horizontal forces will be carried almost exclusively by the walls and may cause an overload of the walls at certain critical areas in the building. Damage and possible failure of the walls may occur. Should the walls be placed in an irregular pattern (e.g. not at every storey), the load transfer may become significantly different from the one which was considered in the basic frame design. Consequently, catastrophic column failures at those storeys where the frame alone provides the lateral-load resistance can be expected.

Using brick masonry not as separate walls but as a fill-in for an entire frame, the earthquake loads will increase because of the basically larger spectral response (greater stiffness and consequently shorter fundamental period) and increased mass. To what degree these fill-in walls or panels will be able to carry these increased loads with little participation of the frame is speculative. Hence, wall damage with even subsequent failure of the frame system may occur. The situation may become even more critical when masonry fill-in walls are placed in an irregular pattern. In that case the force transfer during an earthquake becomes most irregular with an increased chance of wall and even column failure.

Should, in general, certain infilled walls not be built from floor to floor, but only over a limited height (e.g. for having light come into a space through a high-placed window), the consequences can become potentially catastrophic. Although the wall could fail, it is more likely, as illustrated in numerous earthquakes, that the effectively short frame columns at the 'window' level will collapse. In fact, these columns have not been designed for such a force exposure and cannot withstand the large concentrated lateral shear forces.

The fundamental problem of introducing brick masonry lies in the fact that the structural system has been altered without recognizing the consequences. The only way to deactivate the structural participation of such walls can be achieved by keeping the wall or panel elements free from adjacent frame columns and upper frame beams (at the floor ceiling). In that case the walls will be free from shear forces and the frame (columns) can deform without restriction. With the wall only connected to the frame at the floor level, soft filler material should be used to fill the gaps between frame and wall. In fact the wall becomes a so-called floating wall – a system typically used for nonstructural wall partitions in buildings in high-seismic areas.

Building interaction

In inner-city blocks, buildings are typically built in direct contact with one another. Although this condition has potentially certain advantages, it also creates conditions which have often led to serious damage. The advantage of immediately adjacent buildings of identical or similar construction is the possibility to resist the earthquake loads jointly; the weaker building may be 'supported' by the stronger neighbouring structures. This behavior is undoubtedly quite different than the anticipated response of free-standing buildings which is the basis for typical design assumptions.

Building pounding

In case adjacent structures are different in configuration, the individual buildings will undoubtedly exhibit different response modes under an earthquake. Such different dynamic characteristics of adjacent buildings lead to a pounding or banging of the two structures against one another. This impacting behavior becomes particularly critical if the buildings are of different heights. In that case the lower building restrains the motion of the taller structure and damage to either structure in the area of impact can be expected. In case the floor levels in the two adjacent buildings do not coincide, the roof level of the lower structure would impact the immediately adjacent column of the taller building and could cause its failure due to one-sided impacting. This column failure may, most probably, lead to the collapse of both buildings as the taller structure collapses on top of the lower building.

On the other hand, in case the floor levels in two adjacent buildings are closely similar in elevation, failures due to building impacting have been observed in the upper storey of the lower building as this structure effectively 'supports' the higher building. Such failure implies that the horizontal shear resistance of the walls and/or columns at the top-storey level of the lower structure has been less than the shear resistance of the corresponding storey in the taller building. In fact, unless the lower building has a very large floor plan as compared to the taller structure, this condition is virtually always satisfied.

Pounding or impacting seems invariably to be a source of potential earthquake-induced damage, as also has been observed in the Roermond earthquake. The only way to prevent such damage is the introduction of a seismic gap which provides a clear separation of the adjacent buildings, particularly when the dynamic response of these structures is expected to be different. Theoretically, the separation should be large enough to accommodate the maximum expected motions of both building at the potential impacting level. Practically, it is essential to provide a significantly larger separation. Experience has shown that a small gap between buildings can not be kept totally free from construction debris and becomes ineffective (causing again a coupling of the two structures). Instead, the best solution, would be to install between the two structures several layers of, for example, styrofoam of a thickness equal or larger than the theoretically required distance.

Coupling of buildings

In certain cases it may be architecturally impossible to separate adjacent buildings or parts of buildings. In that case it is absolutely essential to connect the several building blocks and design the system as a coupled structure with special attention being paid to both the design of the connections between the coupled blocks and the connection-force transfer into the coupled building blocks. Failing to follow such a design approach leads potentially to serious damage. The observed behavior of many churches in the Roermond earthquake, particularly the historic ones, is a sad testimony of the consequences when these basic engineering concepts are not being followed. In fact, the performance depends on the overall layout of the church.

A modern church with a single rectangular plan for the nave may behave well, provided the walls are prevented from moving outward due to the dynamic earthquake forces acting normal to the wall. Such outward movement can be prevented by tying the surrounding walls to the roof trusses. In fact, even the performance of old churches with steel tie rods across the nave to interconnect the outer walls has been found to be very satisfactory. For the end walls it is also necessary to connect the walls to the roof structure. Failure to do so may lead to a collapse of the gable wall sections in the front and back of the church.

The addition of separate spaces immediately adjacent to the main body of the church, e.g. for the baptistry, sacristy or chapel may be a source of future damage. Such additions should be fully tied-in with the main structure and require a local strengthening of the walls of the main church section through wall columns, cross walls or wall framing. Without such measures, damage in the walls near the junction of main hall and addition may occur. In that case, a separation of the appended structure during the early seconds of the earthquake may be followed by a subsequent impacting between the two parts, which may result in considerable damage to, potentially, both structural parts.

Particularly, a belltower connected to the main structure can lead to serious damage during an earthquake. The presence of a tower located at the corner of the main structure, with two walls coinciding with the corner walls of the hall, leads most likely to both translational and torsional motions of the tower under the earthquake. Such motions may cause a separation (cracking) of tower and church and results in damage to the tower and church walls near the junction. Also, with the tower rising typically above the main church, the difference of the stiffness of tower and church structure may cause damage to either or both structures at their uppermost junction. At that level it is essential to design both elements with sufficient strength in order to resist effectively the concentrated earthquake-induced forces at that level.

Another region of concern for architect and engineer is the uppermost portion of the belltower, where the bells are located and large wall openings are common. The sudden reduction of both stiffness and resistance may lead to very serious damage and possible collapse of the upper tower portion (with possible damage to the roof of the main structure). It is essential that the open tower structure is designed with full consideration of the potential earthquake response. The stiffnesses of the different column and/or wall elements at that level should be fully considered in distributing the dynamic forces. In turn, the resistance of the individual elements should be sufficient to resist the earthquake without damage. Failure to consider these principles may have serious consequences.

Instead of connecting the belltower to the main body of the church, it is also possible to separate the tower from the main structure. Such a structural separation would eliminate the interactive damage potential. However, the design of the upper portion of the belltower remains critical if damage at that level is to be prevented.

Against the background of the considerations noted in this section, the damage to numerous churches in the Roermond earthquake should come as no surprise (Meidow & Ahorner 1994). Particularly, in the case of historic churches, the structural development of such churches over the centuries increases the vulnerability to earthquake damage. Historically, a church may have started as a chapel before larger portions, including possibly a belltower, were added over the centuries. In many regions of the world this process has taken place without paying attention to possible earthquake exposure. However, such a history of construction without tying the different portions together in order to have the system respond as an integral unit, can only lead to serious damage under an earthquake. Preventing damage of historic buildings due to earthquakes in general requires a strengthening of such structures (UNIDO 1984). Developing strengthening procedures requires detailed knowledge about the structural resistance and a profound understanding about the anticipated response. Modern construction technologies offer many effective procedures to protect our historic heritage. Failure to strengthen such structures may lead to irrepairable damage.

Conclusions

Although the damage caused by the 1992 Roermond earthquake occurred over a wide region (Haak et al. 1994), its extent can be termed light to moderate. The appearance of soil instability and soil liquefaction points to the potential danger of developing the low-level river-front regions along the Maas and other rivers in earthquake regions for housing or other high-density construction.

Rather than focussing on the use of typical earthquake code provisions for future construction in a basically low-seismic zone like the Roermond region, it is proposed to direct specific attention to the architectural form and layout of future buildings and develop an awareness of the potential earthquake response characteristics of buildings and other structures (e.g. AIA Research Corporation 1975, Arnold 1989). To that effect, the consequences of errors in both the horizontal-plan and vertical layout of buildings are presented with the aim of guiding future earthquake-resistant design. It is proposed that local and regional building authorities develop simple guidelines based foremost on architectural design consideration. Such guidelines should also cover simple design-load values for the earthquake-resistant design of different typical building categories as reflected by the regional building inventory.

The risk of using brick-masonry walls as nonstructural elements in framed type buildings has been discussed, as well as the potentially dangerous use of brick infill walls in concrete or steel frames designed to resist the full earthquake loads. Practical guidelines to prevent pounding of adjacent structures are presented. Also, the design needs to achieve the essential integrated behavior of buildings with a highly complex plan layout, such as churches, through an effective coupling of the several building elements, have been discussed. In general, in case the planning and earthquake-resistant design of future buildings would be guided by appropriate site selection and specific architectural considerations, as discussed in this paper, the seismic risk could be reduced substantially.

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