SITING OF ADOBE STRUCTURES IN EARTHQUAKE PRONE AREAS

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ABSTRACT

Adobe and mud structures, used widely for housing in earthquake prone areas throughout the world, will fail, even in the presence of good design and workmanship, if they are built on poor sites. Structural and seismic factors, topographic factors, and lithologic factors are all important in selecting geologically safe construction sites away from fault zones, cliffs, unstable slopes, or areas with deep alluvial or man-made fills.

Introduction

Adobe or mud structures are widely used for low cost housing and public buildings in regions where wood or other building materials are not available because of either high cost or scarcity. Throughout many of these regions, e.g. along the western margin of the Western Hemisphere or in the Middle East, earthquakes are a frequent occurrence. The use of mud as a building material in seismically active (i.e. earthquake prone) areas has resulted in hundreds of thousands of human deaths and billions of dollars in property losses in recent years as reflected by the following single report from the Earthquake Information Bulletin—typical of many each year.

> "Southern Peru experienced a destructive earthquake on February 16 (1979). The magnitude 6.7 earthquake was located about 100 km northwest of Arequipa, where at least 14 persons were reported killed, many were injured, and damage to adobe-type homes was extensive" (1).

Many of these deaths and some of the property losses are preventable, even if adobe (one of the weakest building materials in terms of earthquake resistance) is used as a building material (2).

Preventable deaths resulting from earthquakes occur every year somewhere in the world. On the average, 10,000 people lose their lives in earthquakes annually (3). In some years, for example in 1976, the number of fatalities totals hundreds of thousands. Ultimately, prevention of such deaths will be possible when we develop an earthquake prediction capability and implement worldwide earthquake warning systems. Implementation of such systems will take years. In the interim, the number of earthquake related deaths can be significantly reduced through appropriate design and construction of structures on relatively safe sites.

Property losses can also be reduced. Between 1926 and 1950, UNESCO estimated an average annual property loss of $400,000,000 (US) (3). These annual losses are increasing with increasing development. Single earthquakes now may cause similar amounts of property loss. For example, the 1960 Chilean earthquakes cost $300,000,000 (U.S.) in housing along (4), the 1964 Alaskan earthquake resulted in $310,000,000 (U.S.) worth of property damage (3), and the preliminary estimates of damage in the 1976 Guatemalan earthquake totaled $1,100,000,000 (U.S.) (5).

Many countries in seismically active regions have initiated programs to reduce losses of life and property. One early step in such programs is to develop seismic risk maps, maps showing areas of relatively high and low risk with respect to potential earthquake damage (6,7,8). In addition, detailed maps may be prepared for areas of special concern (e.g. major cities or seaports) (9). These maps provide a base for the detailed geological and engineering studies necessary for thorough site selection analyses.

The value of seismic and earthquake engineering studies, especially in less developed countries (LDC's), was underscored by Flores (4). Earthquakes can create damage worth the equivalent of the national budget of an LDC. Flores indicates that regulation of construction in Chile prior to the 1960 earthquakes resulted in a 25% ($100,000,000 U.S.) decrease in damage relative to pre-regulation projections. Had all houses conformed to applicable standards, losses would have been reduced by 75% or $300,000,000 U.S.

Damage to the spirit of the people can also be prevented through reduction of losses in property and life. A loss of morale can critically influence development efforts, reconstruction and economic growth of a country and should not be ignored. In this paper, I delineate criteria for selecting safe building sites in seismically active areas, as one facet of an approach to reducing property damage, loss of life, and resultant loss of morale. Safe siting is particularly important where adobe is used in building, because adobe fails readily under the influence of ground shaking and other effects of earthquakes.

Both pre- and post-earthquake siting projects are feasible. However, the inertia to change limits the impact of pre-seismic siting, as such projects usually influence only new structures. Post-earthquake projects, as part of disaster relief programs, may have wide impact, as the population is open to change and is in need of reconstructed buildings. In either case, site selection is critical to development of earthquake resistant buildings.

Damage Produced By Earthquakes

The wide range of geological effects of earthquakes have been reviewed by many authors (3, 10, 11, 12). Among the most important effects are ground rupture, landslide, earth lurch, liquifaction and settling of soil, and flooding.

Ground ruptures result from several causes. First, surface faulting may produce a series of discontinuous cracks (13). The surface may be offset along such cracks in both vertical and horizontal directions. Such offsets may range from a few centimeters to several meters. Ground rupture also occurs in cases of lurching and landsliding. Some of the most spectacular cracks developed by the 1976 Guatemalan earthquake were developed at the heads of landslides, where cracks more than a meter across and several meters deep, with vertical offsets of several meters, created a greatly disrupted terrain.

Landslides develop where slopes are oversteepened, either for natural or artificial reasons. Where streams undercut slopes, especially where minor faults and joints are present in the bedrock, the landslide potential is significant. Road construction, home and building construction, and other human activities may also result in undercut slopes. Both natural and human activities led to landslides in the 1970 Peruvian earthquake and the 1976 Guatemalan earthquake (11, 13).

Weak soils and alluvial deposits especially those saturated with water as a result of heavy rains or a shallow water table, may give way to produce landslides on steeper slopes or they may liquify in flat-lying areas. In addition, loose materials may be consolidated by shaking during an earthquake and settle.

Floods may develop both upstream and downstream from landslide dammed rivers and streams. The upstream floods are local and result from the lake which forms behind the dam. The downstream floods may be catastrophic and widespread, if a weak, landslide dam collapses releasing the water trapped in the lake. In addition, debris added to streams by landslides can lead to increased sedimentation and related problems during flooding.

Damage to human constructions as a result of shaking and the various geological effects ranges in extent from widespread in major earthquake (magnitude >7) to local in smaller earthquake (magnitude 3.5-5). Damage may affect large and small structures of modern or ancient design and may range from simple cracks to total collapse. Figure 1 shows typical failure lines in an abode structure. Both adobe and modern steel-reinforced buildings will suffer damage, if weaknesses in design, workmanship, materials, or siting exist.

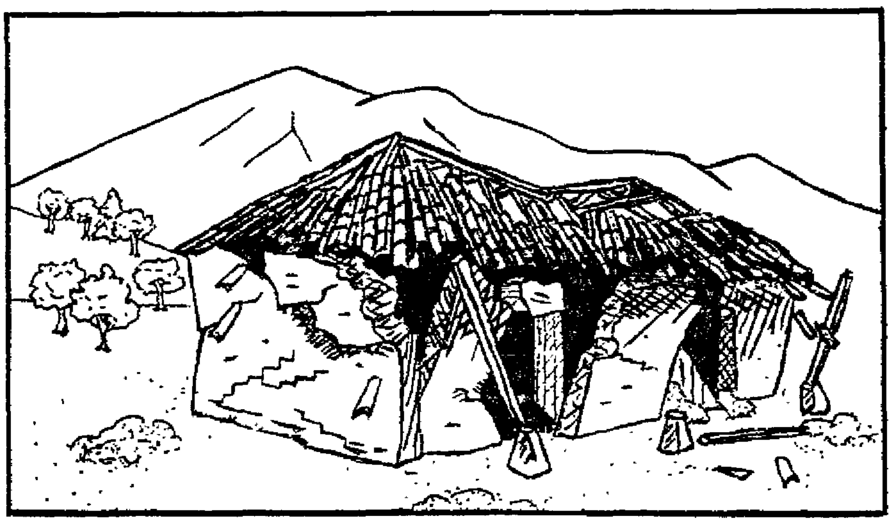

FIG. 1

Sketch of earthquake-damaged adobe house showing typical failure including diagonal cracks fallen tiles, and partially collapsed roof (after Raymond et al. in ref. 2).

Site Selection Factors

Factors important in selecting safe construction sites, whether they be sites for single houses or sites for entire towns, may be categorized into three groups — structural and seismic factors, topographic factors, and lithologic factors. In long range programs of construction or reconstruction, all factors from each group should be evaluated by a team of geologists and engineers. Where this is not possible, paraprofessionals, trained by a knowledgeable instructor, may use a set of detailed guidelines to select sites which are devoid of obvious flaws (14).

Structural and Seismic Factors

The seismicity of an area, both recent and historical, is of critical importance in site selection. Studies of recent earthquakes can provide evidence for evaluation of: (a) the location of active faults; (b) the maximum ground acceleration (shaking) expected in a given area; (c) the type of damage (Mercalli intensities) expected on different foundation materials and for different structures for earthquakes of varying magnitude; and (d) the short term frequency of damaging earthquakes. These recent data can then be combined with historical data to provide a historical record of damaging earthquakes and, with geological data, an estimate of the design earthquake, the earthquake which would give the most severe shaking at a given site (3).

Seismicity should not be estimated solely on the basis of historical earthquake activity, however (15, 16). Topographic, lithologic, and structural data can reveal pre-historic (Holocene and Quaternary) activity on faults. The data expand the seismic record for an area and allow a more thorough analysis of seismic risk, as virtually all large earthquakes (Magnitude >6.0) occur on faults recognizable through field studies (16). Thus, active faults may be recognized on the basis of geological, as well as geophysical evidence.

In the United States, the Nuclear Regulatory Commission has defined "capable faults." These are faults thought to be "capable of causing movement at or near the ground surface or generating high vibratory ground motion" (17). The recognition of a capable fault depends on seismic and geological evidence, as capable faults are defined as those faults with recurrent movement history in the past 500,000 years and/or tectonic activity within the past 35,000 years (17). Because historical records extend for only a few hundred or thousand years, geological studies, based on field work, clearly contribute to thorough seismic risk analyses and site selection.

Geological field studies reveal a multitude of important features. For seismic risk studies, evaluation of length of fault rupture is important in estimating Richter magnitude (3, 18). Offset stream channels, faulted alluvial and other Quaternary deposits, fault scarps, and sag ponds provide evidence of recent and potentially active or capable faults and should be included in the seismic risk analysis.

In terms of site selection, data indicative of an active or capable fault are important in evaluating the geological structure of an area. Such evidence should be summarized on a geologic map, which, like the seismic risk map, provides a basis for detailed site selection studies. The geologic map should also include data on the age of rock units offset by faults and careful plots of all landslides.

Using the seismic risk and geologic maps as a basis, the geologist and engineer can evaluate the area in which a site is to be selected. Structural features that should be evaluated in the local study include faults and joints. Recognition (and mapping) of the exact location of active or capable faults in the area, location of older faults and their related features, and evaluation of joint systems are all aspects of a thorough analysis. Active or capable faults and the associated zones of crushed rock must be avoided as building sites, as rupture may occur anywhere within the fault zone, destroying structures built on the line of fracture (e.g. 12). In addition, the crushed rock materials along the zone provide poor foundations. Dead or inactive faults should also be avoided, as these fault zones also contain weak foundation materials. Furthur, some faults, such as the San Andreas fault of California, have a long history of movement (19) and others have presumably been reactivated during later tectonic events (e.g. 20).

Criteria useful for the recognition of faults have been summarized by many authors, including Billings (21). Structural features of note include:

(a) offset rock layers;
(b) truncated rock layers;
(c) slickensides; and
(d) zones of gouge, breccia, mylonite, or "horses".

Zones containing such features must be rejected as building sites (Figure 2).

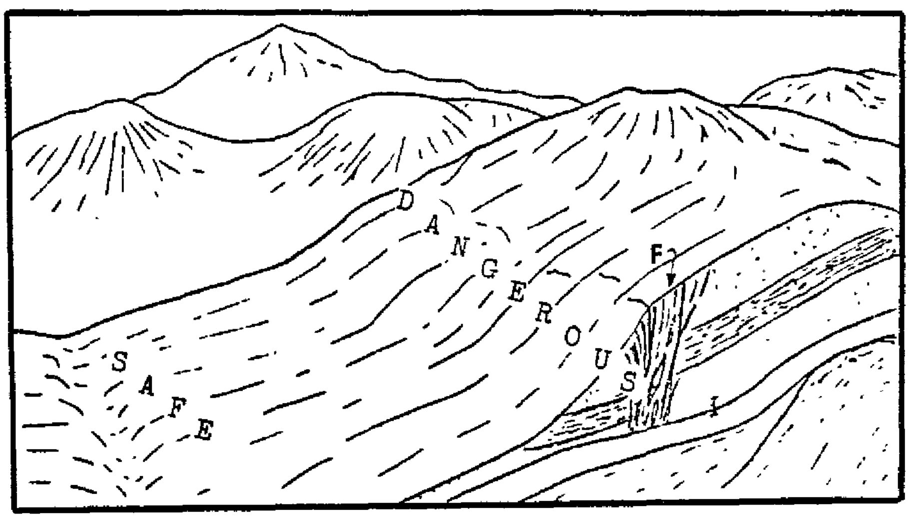

FIG. 2

Sketch showing dangerous building sites along a fault zone (F).

Joints are fractures along which no significant movement has occurred. However, highly jointed bedrock does not provide a strong foundation for a structure. In addition, where joints are arranged so as to weaken slope materials, they may lead to landslides. Consequently, it is important to examine potential sites for flaws imparted by jointed rock.

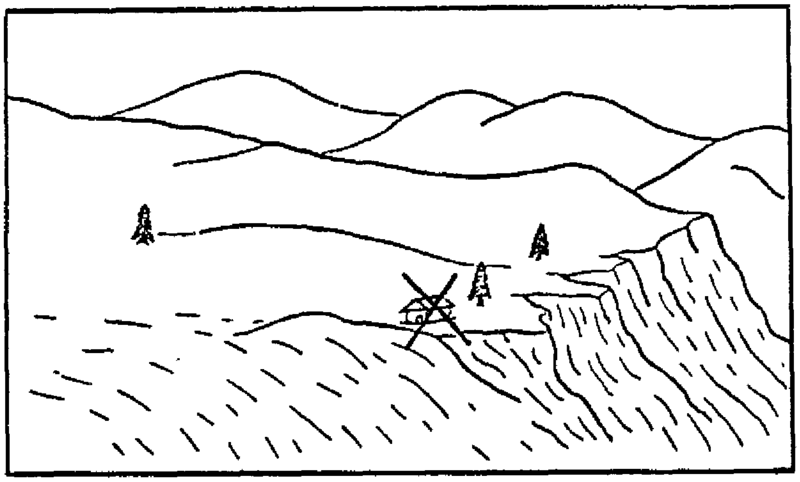

FIG. 3

Sketch showing unsafe building site (X) along cliff face.

Valley bottoms may also be hazardous. The hazard at such sites is only indirectly related to the topography. Landslides from above provide one type of hazard, especially in narrow, steep walled valleys. The second type of hazard is related to the lithology of the rock or soil in the valley bottom. It is well known that poorly consolidated materials lead to increased earthquake damage (12,25,26). Ground shaking on alluvial materials, as reflected by accelerations, may be increased up to 4.3 times, versus accelerations on adjacent bedrock (27). Thus lithologic factors must be evaluated at such sites.

Valley bottoms may also be subject to flooding. For example, the 1976 Guatemalan earthquake produced landslides that dammed at least four major rivers. The 1970 earthquake produced a similar phenomenon in Peru (11). Landslide dams produced flooding upstream and, if they subsequently collapse, flooding also occurs downstream. Although accounting for the flood factor is difficult because of the many potential sites for landsliding along major rivers and streams, where nearby slides or areas of potential sliding occur, they should be taken into account during the site selection process.

Lithologic Factors

The importance of the lithology of the foundation material at building sites is very important. Solid bedrock provides the best foundation for structures. That damage increases with decreasing strength and cohesion of foundation materials has been revealed by numerous post-earthquake studies (28-31). Therefore, a thorough site selection study should include a civil engineer's or soil scientist's study of the soils and/or a geologist's evaluation of the bedrock, depending on local conditions.

Topographic Factors

The topography—the relief, contour, and slope of the land—can provide many clues to the relative safety of a site. Topographic factors relate to site safety in two ways. First, many topographic features reflect underlying faults. Second, certain sites are unsuitable for construction in seismically active areas because of the topographic considerations alone.

Underlying faults are expressed in the topography by a variety of features. These include offset stream valleys and ridges, truncated ridges (spurs), fault scarps and fault-line scarps (localized steep linear slopes), linear series of springs, linear groups of marshes or ponds (sag ponds), visible zones of surface cracking or offset of man-made objects (e.g. roads or canals), and topographic lineaments such as unusually straight stream or river valleys. Prospective sites should be examined for such features and sites along the line of any group of such features should be avoided.

In addition to the topographic factors listed above, i.e. those that reflect underlying faults (or joints), sites in certain topographic situations should be avoided for reasons of their own. The Guatemala earthquake of 1976 produced thousands of landslides, many of which resulted in loss of life and property. In Peru, the potential hazard posed by landslides is well known, in part as a result of the Huascaran debris avalanche that buried Yungay (11). Therefore, sites immediately above, within, or below presently developed landslides should be avoided. In addition, sites should be avoided where the landslide potential is great as a result of structural factors (e.g. extensive faulting or jointing), stratigraphic factors (e.g. jointed resistant rock masses overlying weak rock masses that are tilted towards a valley), and topographic factors (e.g. oversteepened slopes).

Relief and slope are critical factors to evaluate in relation to the potential for earthquake generated landslides at a site. In Guatemala, many lives were lost where structures were erected adjacent to cliffs, very steep slopes, or large gullies (barrancas). For example, at Estancia de la Virgen near San Martín, reportedly eleven families were carried with their homes into the Rio Pixcayá when the cliff adjacent to the river collapsed during the earthquake. In Guatemala City, residential areas adjacent to barrancas suffered more intensive damage than surrounding areas, probably as a result of amplified ground motion. Here, some individuals lost their lives as a result of landsliding. As a general rule, construction adjacent to cliffs or barrancas or on or near slopes steeper than 35^{o} (75% grade) should be avoided (Figure 3).

Sites on high and especially narrow ridges should also be avoided. High and narrow ridges are known to experience ground shaking amplified up to three or more times that of adjacent valleys (22,23,24), which results in greater damage. In addition, narrow ridges are subject to landslides on both sides, a condition developed during the 1976 Guatemalan earthquake in Las Venturas (San Martín), along the San Martín-Chimaltenango road, and along the El Tablon-Las Flores road.

Hard crystalline rock types provide much firmer foundations than poorly consolidated sediments or pyroclastic rocks. Many of the landslides in Guatemala occurred in weak pyroclastic materials which crumbled on shaking. Glaciofluvial and other similar deposits of the Rio Santa Valley of Peru are subject to similar failure (11). Granitic rocks, gneiss, metasandstones and similar rocks are preferred as foundation materials to sedimentary rocks. In general, poorly consolidated, weak, wet, organic-rich soils or alluvial deposits should be avoided.

Where sites must be selected in alluvial materials, thin, well compacted dry soils with silty layers provide better foundations than the wet, poorly consolidated soils. Thixotropic clays and highly saturated sands, even at considerable depth below a building site, will make the site unstable and subject to settling or sliding. Turnagain Heights, Alaska, where a whole section of houses slid towards the sea, was constructed in an area with underlying thixotropic clay (10).

Conclusion

Safe building sites will allow well constructed adobe structures to survive earthquakes without total collapse. A thorough investigation of proposed alternative building sites should be used to eliminate sites from consideration that occur along fault zones, on highly jointed and/or steep slopes, along cliffs or roadcuts, in areas of previous or potential landsliding, along narrow ridges, in areas of extensive natural and man-made fill, and along narrow valleys near large cliffs or landslide prone slopes. If adobe structures are constructed using proper design, good workmanship, and good materials on safe bedrock sites lacking these flaws, loss of life and property will be minimized.

Site analysis is best carried out by trained engineering geologists. However, in LDC's there is often a shortage of trained personnel. Under such circumstances, locals trained as paraprofessionals (using graphics and simple rules) may make site evaluations for adobe structures that will eliminate the worst sites from consideration.

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