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CONTROL OF HAZARD DUE TO SEISMICITY INDUCED BY A HOT FRACTURED ROCK GEOTHERMAL PROJECT

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ABSTRACT

In 2003 hydraulic stimulations were carried out in a geothermal field in eastern El Salvador, Central America, as part of a project to explore the feasibility of commercial hot fractured rock energy generation. A key requisite for this environmentally-friendly energy source is that the fracturing of the hot rocks at depths of 1-2 km must not produce levels of ground shaking at the surface that would present a serious disturbance or threat to the local population. Thresholds of tolerable ground motion were inferred from guidelines and regulations on tolerable levels of vibration and from correlations between instrumental strong-motion parameters and intensity, considering the vulnerability of the exposed housing stock. The thresholds were defined in terms of peak ground velocity (PGV) and incorporated into a "traffic light" system that also took account of the frequency of occurrence of the induced earthquakes. The system was implemented through a dedicated seismograph array and locally derived predictive equations for PGV. The "traffic light" was used as a decision-making tool regarding the duration and intensity of pumping levels during the hydraulic stimulations. The system was supplemented by a small number of accelerographs and re-calibrated using records obtained during the rock fracturing.

Keywords: induced seismicity; seismic hazard; geothermal energy; hot fractured rock; vibration thresholds

1. INTRODUCTION

Seismic activity can be induced by many human activities, including reservoir impounding, high-pressure pumping of fluids into the ground for waste disposal or fracture stimulation, extraction of natural gas and hydrocarbons, or mining. Reservoir-induced seismicity can include earthquakes of moderate magnitude, generally occurring several months or years after impounding is complete (e.g. Guha, 2000). With other activities, particularly those associated with injection or extraction of fluids, the temporal correlation between the operation and the induced seismicity is usually, although not always, much closer. This can allow the operators to adjust or suspend the activity if the rate and magnitude of the induced earthquakes is exceeding, or in danger of exceeding, the tolerable thresholds. Hazard assessment in such situations is very different from that associated with natural seismicity.

Seismic risk is generally understood as the convolution of seismic hazard (primarily, the probability of a particular level of ground shaking) with exposure (people, buildings and infrastructure), the degree of damage or loss depending on the vulnerability or susceptibility of the exposed structures. In earthquake engineering, the premise is that the hazard due to earthquakes cannot be altered and therefore it is assessed quantitatively in order to guide risk management decisions about solutions that involve reducing either the exposure (through relocation) or the vulnerability (through earthquake-resistant design). In contrast, with induced seismicity the option exists to manage the risk through control of the hazard, possibly without intervention in any aspect of the exposure and its vulnerability.

Although the problem of hazard associated with induced seismicity has, by necessity, been a consideration for hundreds of projects around the world, there are no published guidelines on how to define or control acceptable levels of induced shaking and no publicly available reports on how this problem has been addressed in projects. In this paper, a control system developed for a hot fractured rock (HFR) geothermal project in El Salvador, Central America, is presented.

2. THE BERLÍN GEOTHERMAL PROJECT AND ITS SETTING

The HFR project in Berlín, in the province (*departamento*) of Usulután of the Central American republic of El Salvador (Fig.1), presented an unusual problem in terms of the possibility of induced ground shaking. The fracture stimulation was only expected to generate small magnitude earthquakes, if any, and the project took place in a region of very high seismic activity that had been strongly shaken by major earthquakes less than three years earlier. However, the need to ensure that the HFR geothermal project would be environmentally friendly in all aspects, and the highly vulnerable nature of the local building stock, made it necessary to consider any perceptible ground motions that might be generated locally by the rock fracturing process.

2.1 Seismicity and Seismic Hazard of the Berlín Area

El Salvador is a region of very high seismic activity, affected by two principal sources of earthquakes: the subduction of the Cocos plate beneath the Caribbean plate in the Middle America Trench, producing Benioff-Wadati zones, and shallow crustal events coincident with the chain of Quaternary volcanoes (e.g. Dewey *et al*., 2004). Large magnitude earthquakes in the subduction zone tend to cause moderately intense shaking across large parts of southern El Salvador, the most recent example of such an event being the M_w 7.7 earthquake of 13 January 2001 (Bommer *et al*., 2002). The upper crustal earthquakes are limited to smaller magnitudes, the M_w 6.6 event of 13 February 2001 being representative of the maximum size of these earthquakes (Bommer *et al*., 2002). However, due to their shorter recurrence intervals, shallow depths and proximity to population centres, upper crustal earthquakes have produced far greater destruction in El Salvador than the less frequent very large magnitude earthquakes in the subduction zone (White and Harlow, 1993).

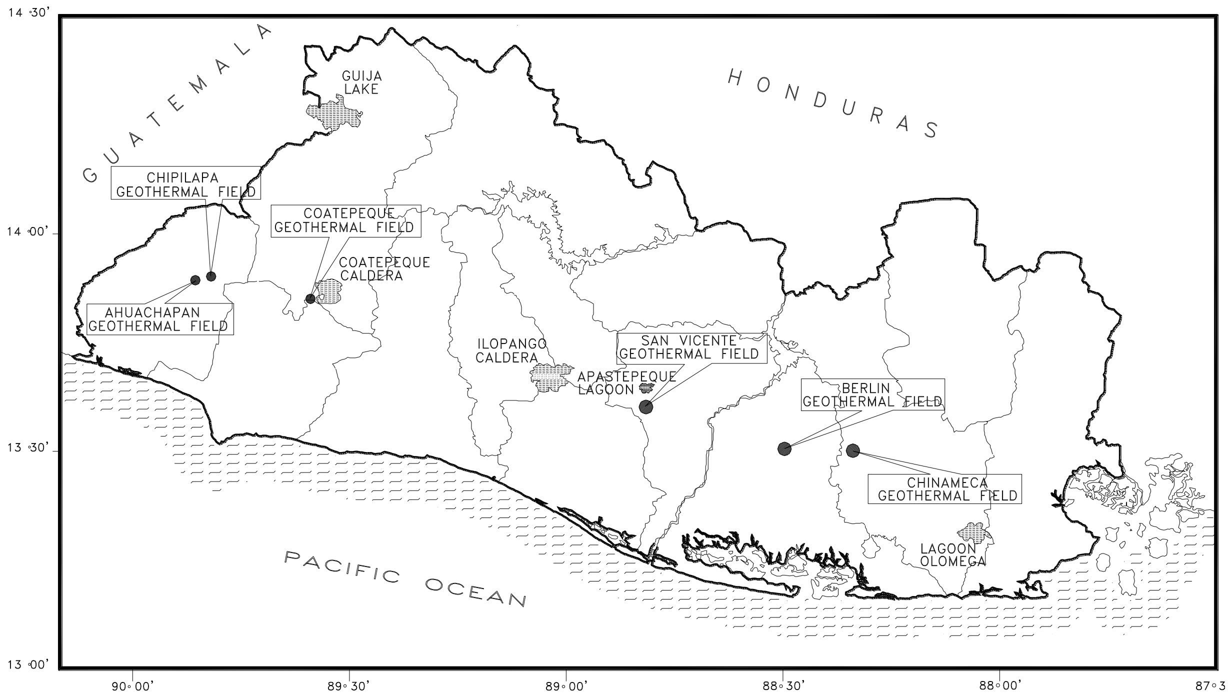

Figure 1. Map of El Salvador showing location of the geothermal fields (Handal and Barrios, 2004)

There are six geothermal fields in El Salvador (Figure 1). The Berlín geothermal field, located on the flanks of the dormant volcano Cerro Tecapa (last eruption thought to have been in 1878), was developed in the 1990s and the current 66MWe (i.e. MW of electricity, the actual useful output) of installed power plant capacity was brought on stream by CEL (Comisión Hidroeléctrica del Rio Lempa), the state electricity company, between 1992 and 2000. Currently, 54MWe are being generated from 8 production wells with the fluid exhausted from the power plant – water at 183ºC – being disposed of via a reinjection system comprised of 10 injection wells. Depths of the field's wells range from about 700 m for some of the shallow injection wells down to some 2500 m for the deeper production and injection wells. More details of the Berlín field can be found in Fabriol *et al*. (1998).

The vicinity of the Berlín geothermal field has not been a focus for the larger destructive earthquakes that have affected other locations along the volcanic chain in El Salvador. To the west of the geothermal field is the area around the San Vicente (Chichontepeque) Volcano, where destructive earthquakes occurred in 1936 (Levin, 1940) and February 2001 (Bommer *et al*., 2002). To the east, and closer to the field, there is another focus of earthquake activity centred on the towns of Chinameca and Jucuapa (located a few kilometres west of Chinameca), where destructive events have occurred in 1878 and 1951 (Ambraseys *et al*., 2001). There have been, however, seismic swarms in the Berlín area, as in many other locations along the volcanic chain, the most recent being in April and August of 1985.

Part of the geothermal field development activities has been the installation of a surface seismic monitoring array – the Berlín Surface Seismic Network (BSSN) – which was brought into use in 1996 to monitor seismicity in and around the field. Since long-term seismic monitoring and extraction from the field started at about the same time, it is difficult to say with any confidence whether the observed seismic activity is triggered by the ongoing geothermal extraction and injection or is itself a manifestation of the hydrothermal activity around the volcano. There is, however, a hint in the BSSN catalogue that increased seismicity rates correlate with increased production and injection rates but this conclusion is itself clouded by chance events: increased production in the field shortly preceded the large earthquakes of 13 January and 13 February 2001 and these events led to a step change in the observed local seismicity rate. The second possibility, that local seismicity is a manifestation of the field's natural hydrothermal state, supports the idea that in a fracture-dominated geothermal field it is only those faults or fractures which are still seismically active that will remain permeable, by virtue of their continued movement, rather than becoming sealed by mineralisation. In this way it can be argued that microseismic monitoring can be used as an exploration tool in a geothermal field area.

2.2 Building Stock in the Geothermal Field

The building stock within the larger Berlin geothermal field consists overwhelmingly of dwellings typical of rural El Salvador, dominated by *madera* and *sistema mixto* (60%). The *madera* (wood) buildings are typically light weight and flexible (even when the heavy roofs represent a danger), and the *sistema mixto* is a fired-brick masonry structure most often strengthened by weakly reinforced beams and columns. The traditional building types are *adobe* and *bahareque*. Adobe is sun-dried clay brick and the very high mass-to-strength ratio of houses constructed from this material makes them highly vulnerable under earthquake shaking (Dowling, 2004). Bahareque is a form of wattle-and-daub, with timber vertical members and a horizontal cane (*barra de castilla*) lattice filled with mud and covered with plaster, comparable to the *taquezal* system used in neighbouring Nicaragua, as well as to the Peruvian *quincha* system and the Japanese *shinkabe*. The seismic performance of bahareque is considerably better than that of adobe, but is severely reduced over time by the action of the climate and insects on unprotected timber and cane elements (Lopez *et al*., 2004).

A detailed survey of the type and condition of the buildings in 13 communities was conducted (Velásquez, 2002). The building stock is dominated by small houses of < 25m^2 area (~70%), and the maintenance is often poor, leaving as many as 50% of the dwellings in a technically poor condition with little resistance to ground shaking. Adobe and bahareque account for 19% of the total building stock in the 13 communities around the Berlín field, but these represent the most vulnerable component of the exposed building stock and therefore the element expected to control the permissible levels of shaking.

The two 2001 earthquakes caused significant damage in the Berlín area. A damage survey was conducted, although this was carried out after 13 February and hence the statistics represent the cumulative effect of the two earthquakes and their aftershock series. All adobe houses suffered some degree of damage, about half being classified as collapsed. Although bahareque buildings performed better, only about 15% of the exposed dwellings constructed from this system survived without any damage. Vulnerability curves for the most susceptible local buildings were derived and these are presented in Section 3.3.

2.3 The Berlín Hot Fractured Rock (HFR) Project

In 1999, CEL's geothermal interests were spun off as a separate company, Gesal (subsequently renamed LaGeo), and in 2001 Shell negotiated a joint cooperation agreement with LaGeo to carry out a HFR trial project. The well selected by Shell's Geothermal Team and LaGeo as the best candidate for an attempted HFR stimulation was TR8A, an injector north of the main production zone, the low injectivity of which was recognised as severely restricting its ability to accept injectate. The objective was to stimulate the subsurface fracture network around the well to increase its permeability thus creating a large capacity heat exchanger at depth: a hot fractured rock (HFR) geothermal reservoir. If successful, this would extend the productive zone of the Berlín geothermal field beyond its current northern boundary.

Studies of the tectonic stress regime in the Berlín area suggested that the fracture network would develop in a NNW-SSE orientation and intersect one of three wells some 500 m away from TR8A. The stimulated well would then become the injector in an HFR doublet with the well intersected by the fractured region being the producer. In such an HFR system, heat can be extracted from the hot reservoir rock by circulation of water from the injector, through the reservoir, to the producer. In this way the project set out to employ the techniques developed at the Soultz-sous-Forêts site in the Alsace, France (see www.soultz.net for an overview of this project) where geothermal exploration and testing has taken place for a number of years. Hydraulic stimulation of well TR8A in the Berlín field was carried out between June 2003 and January 2004.

3. DESIGN of TRAFFIC LIGHT

The main focus of earthquake engineering is the prevention of structural and non-structural damage, the basic criterion being to ensure life safety and then beyond this to limit economic losses and business interruption. For vibrations induced by anthropogenic sources, be they machinery operation, pile driving, traffic or micro-seismicity, structural and non-structural damage continue to be vital performance criteria but additionally there is the issue of human discomfort. If induced vibrations cause disturbance or distress to those living or working in proximity to the source of the excitation, it is likely that there will be complaints or protests, which, depending on the legal framework of the country in question, could lead to suspension of the activity or litigation resulting in financial compensation to those affected.

The specific context and conditions of the Berlín HFR project required the development of a calibrated control system, dubbed "traffic light", in order to enable real-time monitoring and management of the induced seismic vibrations. An important factor in this case is the high natural seismicity of the region and the fact that it is perfectly feasible for an earthquake to occur during or after the pumping operations without any direct connection to the injections. The most delicate issue would be if damage occurred due to such a natural earthquake because it would be difficult to establish the degree to which the damage was exacerbated by weakening of the houses in the area due to any ground shaking induced by the injection process up to that time. Similarly, if a natural earthquake causes damage, the vulnerability assessment that has informed the baseline seismic risk assessment and the upper thresholds on the "traffic lights" may need to be revised. Cypser & Davies (1998), in their discussion of liability under US law for the effects of induced seismicity, state the following: "*Seismicity induced by one source might accelerate failure of support originating from another source, leaving both of the parties at fault proportionally liable to the injured parties*".

3.1 Conceptual Framework

For real-time risk management of induced vibrations, two features are deemed to be important. The first is the ability to estimate the intensity of any induced vibrations with as little delay as possible, so that these can be compared with the pre-established thresholds and used to guide decision making. The second feature is that it must be possible to verify unambiguously the induced levels of motion. Both of these criteria exclude the use of macro-seismic intensity as the control parameter: its assessment is time consuming, practically impossible at night, and the intensity of one event becomes very difficult to assess if it is closely followed by another. Moreover, intensity is determined subjectively and therefore would be problematic to settle disputes regarding the level and impact of induced ground vibrations. The solution is to use instrumental measures of ground motion, and in the case under consideration the ideal mode of operation was identified as using two complementary instrumental arrays (Section 4.1).

A system is ultimately needed that can, in effect, be operated as a “traffic light”, allowing those on site to determine, simply and rapidly, whether it is possible to proceed (green), to invoke caution (amber), which may mean adjusting levels of operation (in this case, the hydraulic injection rate), or simply to stop (red).

3.2 Human Susceptibility to Ground Motions

Ground motions can be expected to become distressing or even intolerable to people in the vicinity at lower amplitudes than those required to cause structural damage (e.g. Steffens, 1974). Therefore, it was recognised in the early stages of the project that the criteria for acceptable levels of ground motions could be controlled by the extent of discomfort and disruption suffered by local residents. There are no published guidelines specifically on the control or definition of acceptable levels of induced seismic ground-shaking; acceptable limits for earthquake-resistant design to avoid structural damage correspond to much higher levels of motions than would be considered disruptive to the local population, hence such guidelines were not appropriate as the basis for the ”traffic light”. It was therefore necessary to look outside the field of earthquake engineering for guidance. This study drew on the large body of national and international standards and guidelines relating to the measurement and limitation of horizontal or vertical vibrations in buildings caused by construction-related activities (e.g. pile driving), drilling, blasting or mining operations, machine foundations and traffic.

Human bodies have their own resonant frequencies, and so all tolerances are frequency dependent. ISO 2631 (ISO, 1989) recommends frequency weighting factors to be applied to measured accelerations. Humans are generally most sensitive to vibrations along what is defined as their ‘z-axis’, i.e. in the vertical direction when standing. Frequency of occurrence as well as the frequency content of the motion is important. A single event of a particular intensity may be felt by the local population without undue alarm, but the tolerable intensity will be expected to decay rapidly with the number of perceptible shaking episodes. Induced vibrations, in order of increasing tolerability to humans, may be either continuous (e.g. machine-induced), intermittent (e.g. pile driving) or transient (e.g. blast-induced). Blast vibrations occurring one or several times a day are probably the closest equivalent source of vibration to small magnitude injection-induced earthquakes in the literature, despite their shorter duration.

ISO 2631 (ISO, 1989) presents modification factors for both duration and daily frequency of occurrence.

Early work by Reiher and Meister (1931) and Dieckemann (1958) into human sensitivity to horizontal and vertical vibrations, mainly those caused by machinery, provides the foundation for many of these studies (e.g. Steffens, 1974). Various classification scales ranging from '*just perceptible*' to *'intolerable'* are defined in terms of frequency, amplitude and duration of vibration (the durations are hours rather than the seconds that would define induced earthquake shaking). Most published guidance suggests that vibrations induced by temporary works are more likely to be acceptable to those affected than indefinite vibrations (e.g. BSI, 1992). Conversely, it is also noted in the literature that the unfamiliarity factor in short-term projects may actually give rise to more adverse comments (e.g. ISO, 1989) and it is generally recommended that good public relations may help to decrease this factor.

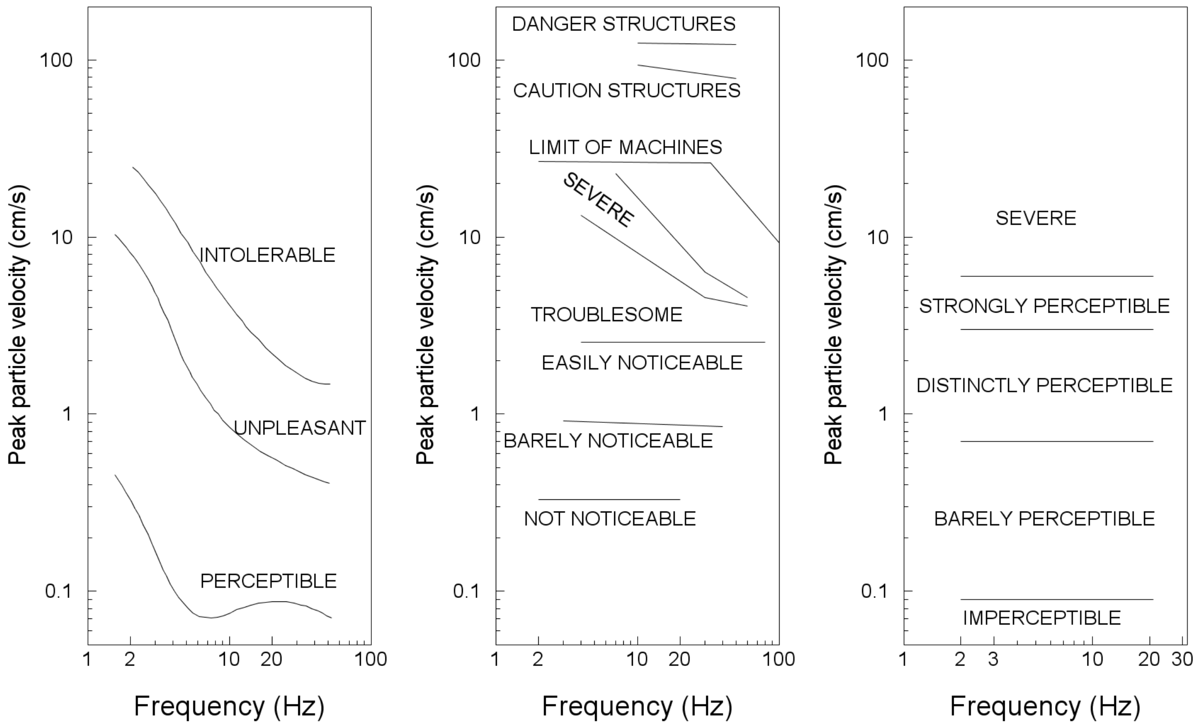

Figure 2: *Left*: Recommended levels of human sensitivity to vibration due to blasting from the USACE (1972); *Middle*: Reference levels for vibration perception and response from traffic, adapted from Barneich (1985); *Right*: thresholds for vibrations due to pile-driving from Athanasopoulos and Pelekis (2000)

Many of the key standards, codes and publications relating to induced vibrations were reviewed to identify both how the vibrations are characterized and how the thresholds are specified. Figure 2 summarizes three different sets of guidelines specified in terms of peak ground velocity (PGV): the US Army Engineering Manual EM 1110-2-3800 (USACE, 1972) for acceptable motions due to blasting; the vibration tolerances for traffic-induced vibrations developed by Barneich (1985) and presented by New (1986); and the paper by Athanasopoulos and Pelekis (2000) dealing with pile driving.

Macroseismic intensity scales, which qualitatively define the strength of earthquake shaking in terms of the effect on humans, objects and buildings, have been reviewed in order to obtain insight regarding the response of humans to earthquake ground shaking. For example, at intensity V, *"many sleeping people awake"* where *'many*' can be interpreted as between 15 and 55% (Grünthal, 1998).

3.3 Building Vulnerability to Ground Motions

A large number of strong-motion parameters have been proposed in the literature as indicators of the destructive capacity of earthquake shaking (e.g. Kramer, 1996). No single parameter is able to capture the destructive potential of ground motion, not least because the relationship between the natural vibration frequency of the structure and the frequency content of the motion is a key factor in determining the response of buildings to earthquake shaking. The Arias intensity (Arias, 1970, 1973) is related to the total energy of the motion; it has been found to be a useful indicator of the capacity of ground motion to trigger landslides (Harp and Wilson, 1995) but for engineered structures the rate at which this energy is imparted by the ground motion is as important as the total energy carried by the seismic waves (Bommer and Martínez-Pereira, 1999).

Amongst the simplest parameters to characterise earthquake ground-motion are those related to measures of peak amplitude. The peak ground acceleration (PGA) is known to be poorly correlated with damage but PGV is a more stable parameter from both engineering and geophysical perspectives. Wald *et al*. (1999) derived a correlation between PGV and Modified Mercalli intensity from Californian data, which was adopted as a guide in this study. The scatter associated with this correlation might suggest that PGV alone is not a robust indicator of the damage potential since high PGV values can occur at low intensities, but it is still a considerably better damage indicator than PGA. The strength of the ground shaking is better represented by more complex parameters that capture other features of the motion as well, such as that proposed by Fajfar *et al*. (1990) which is a function of PGV and the duration. However, for an operational monitoring system such as that required for the Berlín HFR project it was considered advantageous to use a simple parameter and amongst simple peak measurements, PGV was selected as the most suitable parameter. PGV is a parameter that is almost as simple to determine as PGA but is of much greater physical significance; very high-frequency pulses of acceleration, which carry very little energy and do not pose a threat to even weak structures, will have large PGA values but will not correspond to high values of PGV.

Based on empirical and global data as well as detailed surveys in 13 communities around the geothermal thield, vulnerability curves for the adobe structures were established (Figure 3). The damage states are specified following FEMA (2004): slight damage corresponds to hairline diagonal cracks; moderate damage to larger diagonal cracks; extensive damage indicates open cracks or the movement of beams and trusses; and complete damage indicates collapse.

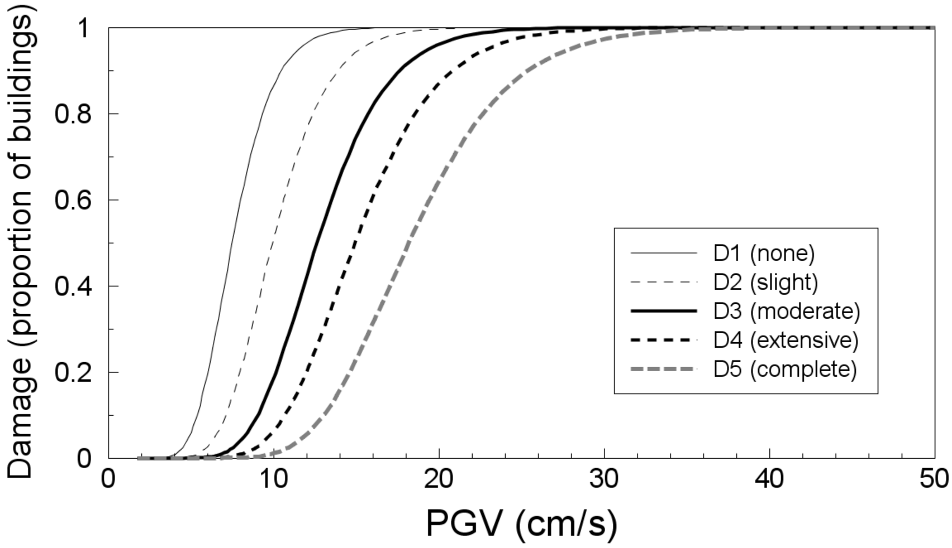

Figure 3. Fragility curves for adobe (sun-dried earthen bricks) dwellings.

The vulnerability of a structure or building type can be estimated deterministically (e.g. through establishment of pushover curves), or empirically based on post-earthquake damage surveys and derived statistics. The approach followed in this study is empirical and largely based on the global damage inventory of earth brick buildings collected and analyzed by Coburn and Spence (2002). Since reliable ground motion estimates are rarely available following large, destructive earthquakes, Spence *et al*. (1992) defined the relative damage distributions and anchored these distributions to the Parameterless Scale of Intensity (PSI). The challenge of the present study was to anchor the relative damage distributions to PGV, this having been chosen as the control parameter for the Berlín HFR project. A linear regression was conducted to relate PSI and PGA (based on data from Spence *et al*., 1992), and a second relation between PGA and PGV, based on the recordings from earthquake swarms in El Salvador (see Section 3.5 and Figure 4) was used to obtain the final values. The fragility curves in Fig. 3 predict damage to adobe houses will commence at a PGV of about 5 cm/s, and for a ground motion of 12 cm/s some 80% of adobe houses will be damaged, with almost 50% experiencing moderate, extensive or complete damage.

3.4 Thresholds of Permissible Motions

Figure 2 illustrates tolerance levels – described qualitatively using different terminology, which thus makes their interpretation somewhat subjective – and the relationship of

Wald *et al*. (1999) indicates that PGV can be approximately equated with the effects of ground shaking as characterised by the Modified Mercalli (MMI) intensity scale. This information has been used to define thresholds for ground motions to cause different levels of disturbance to local inhabitants and pose different levels of threat to their dwellings.

The first step was to estimate the likely dominant frequency of any ground motions that might occur due to the HFR project. Accelerograph recordings (section 3.5) of small-magnitude earthquakes were used for this purpose, particularly those recorded in the 1985 swarms in Berlín and Santiago de María. The response spectra from these recordings consistently showed a pronounced peak at a period close to 0.1 second, hence 10 Hz was adopted as the central frequency and used to infer thresholds from Figure 2. This may appear to be a rather high frequency for buildings but it is appropriate to the heavy low-rise dwellings under consideration.

Table 1. Preliminary proposal for “traffic light” thresholds.

PGV ($cm.s^{-1}$)	Description of Response
0.1	Just perceptible (weak shaking, no damage)
0.65	Clearly Perceptible (light shaking, no damage)
1.3	Disturbing (moderate shaking, very light damage)
3.0	Frightening (strong shaking, light damage)
6.0	Alarming (strong shaking, damage in weak structures)
12.0	Damaging (severe shaking)

The final stage was then to infer a series of thresholds based on those indicated in Fig. 2 for lower levels of shaking (controlled by human response), and from Fig. 3 for the higher levels (controlled by structural damage). In both cases, the inferred levels were checked against the implied intensity levels for each PGV threshold, and the consequent human or structural responses, using the data and relationship of Wald *et al.* (1999). There was inevitably a significant degree of ‘expert judgement’ involved in making these inferences and in the face of uncertainty, conservative decisions were made; this was particularly the case since, as explained later, the “traffic light” operated on the basis of median predicted PGV values and did not take account of the aleatory variability in the ground-motion prediction.

3.5 Predictive Equations for PGV

In order to operate the near real-time “traffic light”, the level of PGV expected at the epicentre needed to be estimated, for which predictive equations relating PGV to magnitude and distance were required. Since it is unlikely that any published ground-motion prediction (attenuation) equations for PGV would be applicable to shallow-focus, small-magnitude earthquakes in El Salvador, new equations were derived for this purpose.

In order to derive the equations, a data set of 115 accelerograms obtained during seismic swarms in El Salvador was compiled. The majority of the records were obtained from the March 1999 and May 2001 swarms in the area of San Vicente, accounting for 50% and 43% of the data set respectively. The remainder of the data was from the 1985 Berlín swarm and an aftershock series in the vicinity of the island Meanguera del Golfo in 1999. The source parameters for all 73 earthquakes were re-calculated by seismologists from SNET (Servicio Nacional de Estudios Territoriales) using data from the El Salvador seismograph network and from accelerograph networks in El Salvador and Nicaragua. The distribution of the data in magnitude-distance space is shown in Figure 4.

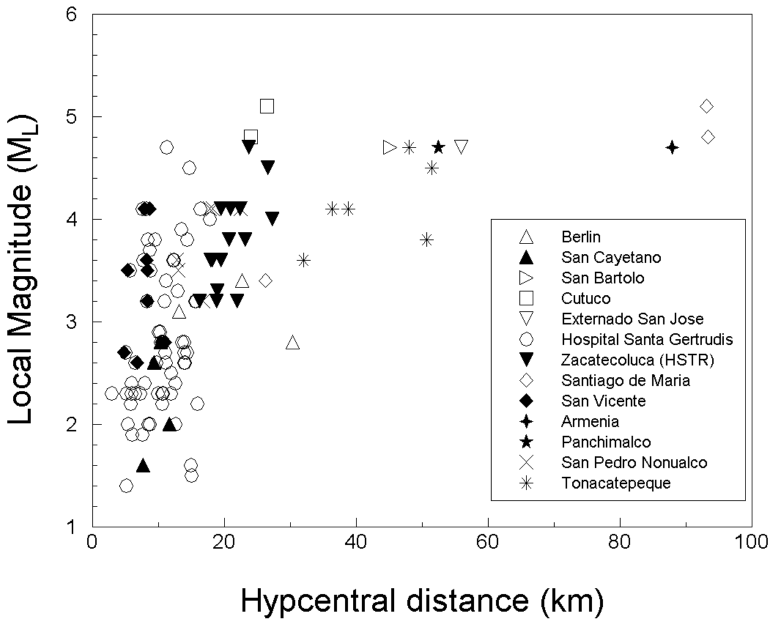

Figure 4. Magnitude-distance distribution of swarm data, indicating accelerograph station from which each recording was obtained. Information on the accelerograph stations is reported in Bommer *et al*. (1997).

The data can be seen to be reasonably well distributed for the small magnitudes expected to be encountered in the induced seismic activity in the Berlín field (M_L < 3.5) although the data is very sparse at the short hypocentral distances of relevance: focal depths of the induced events would be expected to be of the order of 2 km. These limitations notwithstanding, these data were considered a superior surrogate for the motions that might be expected from the induced seismicity compared to equations derived from general predictive equations from other parts of the world.

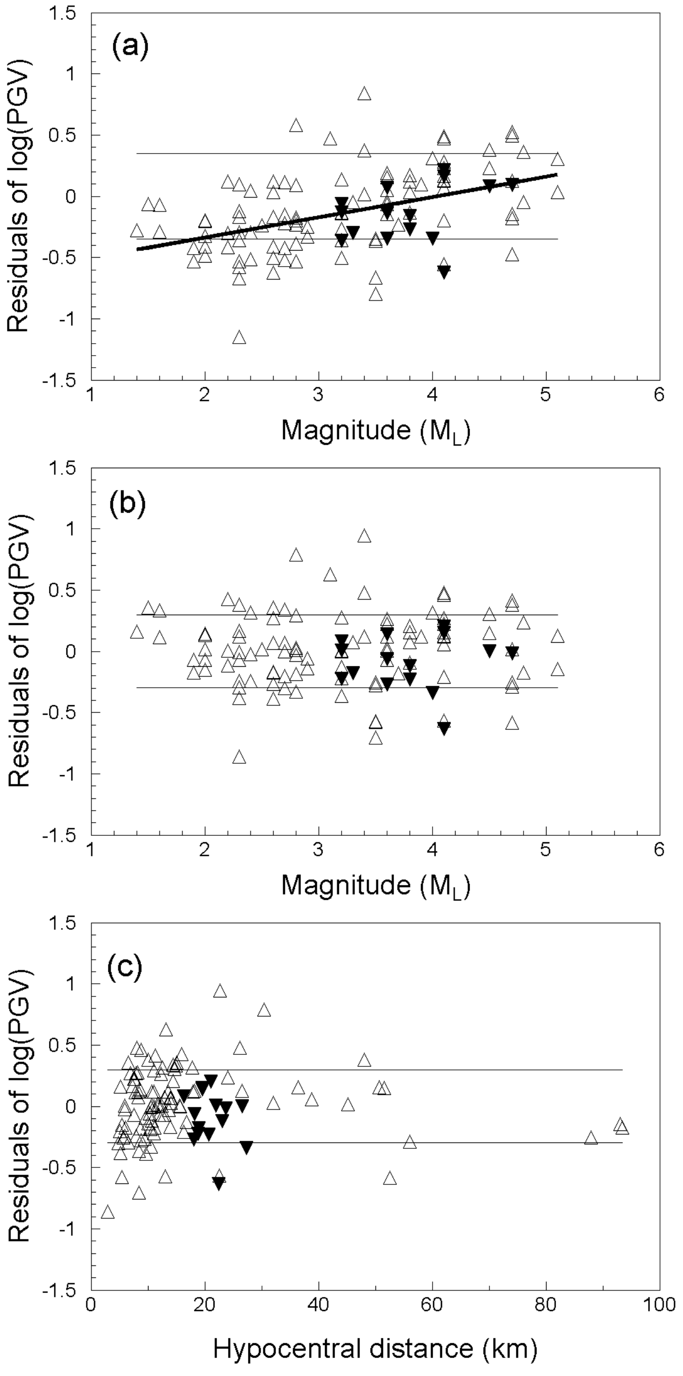

Figure 5. (a) Residuals of PGV values from swarm records determined with equation of Tromans and Bommer (2002), showing trend as thick line; thin lines show the standard deviation of the original equation. Residuals calculated with Eq.(1) plotted against (b) magnitude and (c) distance, together with new standard deviation. The black triangles represent records from the HSTR station (see Section 4.3).

The magnitude-distance distribution of the data was not considered adequate to constrain the magnitude-scaling and attenuation with distance of PGV hence rather than perform direct regression analyses to obtain equations, the approach adopted was to use this data to adjust an existing equation. The selected equation was that of Tromans and Bommer (2002), derived from European accelerograms and predicting PGV as a function of magnitude, distance and site classification. There is no particular reason for selecting this equation and certainly no direct similarities between Europe and Central America were assumed, but the equation is only required as a starting point from which to make adjustments to obtain a local equation. From amongst the relatively limited number of published equations for PGV, Tromans and Bommer (2002) uses one of the simplest functional forms. Subsequent to the project, new equations have been derived specifically from recordings of small magnitude earthquakes (Frisenda *et al*., 2005; Bragato and Slejko, 2005), which may have been more appropriate selections for the starting point, but these were not available at the time the analyses were carried out.

There is insufficient information regarding the geotechnical profiles at strong-motion recording stations in El Salvador for site classification to be included as a variable, so the new equation was derived as a function of only magnitude and distance. The procedure was to calculate the residuals for all the records using the Tromans and Bommer (2002) equation for stiff soil sites, and then to plot the residuals against magnitude (Figure 5a). A linear trend line was fit to the residuals and then added to the original equation, resulting in modified values of the constant term and the coefficient in the magnitude term:

$$log(PGV) = -0.527 + 0.521M_L - 1.058 log(R) \quad (1)$$

where PGV is in cm/s and R is the hypocentral distance in km; the standard deviation calculated from the residuals of the adjusted equation (Figure 5b) is 0.297, smaller than the value of 0.35 obtained by Tromans and Bommer (2002).

The final step was to then calculate the residuals with the modified equation and to plot these against distance (Figure 5c), from which it can be appreciated that there is no tendency and hence the equation is considered to be well adjusted to the data.

3.6 A "Traffic Light" for Operation of Inducing Activity

A significant amount has been written in the open literature on induced seismicity associated with engineering activities such as fluid injection, the impounding of reservoirs and mining (e.g. Talebi, 1998; Guha, 2000; Knoll, 1992; Cypser, 1997). These studies tend to be based on an assumption that all induced seismic activity is undesirable and then focuses on the question of whether or not an activity carries a risk of triggering seismic events. In HFR reservoir stimulation activities, a more difficult question is faced: given that the aim is to generate seismic events in order to enhance the permeability of the reservoir fracture system, how can it be ensured that the stimulation activities will generate only *micro*-seismic events, small enough not to produce ground motions that exceed the specified thresholds?

For the induced ground motions to be considered acceptable or tolerable, consideration of the exceedance or otherwise of a single amplitude threshold is probably not sufficient. A single occurrence of perceptible ground shaking, even with a relatively high PGV (provided this is below the threshold for structural damage), may be far less alarming to local inhabitants than a sustained series of weaker, but still perceptible, motions. An alternative approach that could be employed instead of a simple measure of the number of perceptible events would be to use a second parameter indicative of the total amount of shaking, such as the Arias intensity or the bracketed or uniform durations above an absolute threshold of acceleration (Bommer and Martínez-Pereira, 1999). This second quantity could be plotted cumulatively on the x-axis and the thresholds of PGV (on the y-axis) for different qualitative degrees of tolerability would decay the further one advanced along the x-axis. This would be analogous to the warning system for rainfall-induced landslides proposed by Aleotti (2004), whereby the intensity of rainfall required to trigger instability decreases with the duration of the precipitation.

In order to validate the PGV thresholds, accelerograph recordings obtained in San Vicente during a seismic swarm of March 1999 were processed and the values of PGV determined. Newspaper reports were then examined for the period of the swarms, which were reported on a daily basis with particular events noted either because they caused alarm or physical damage. Although the locations referred to in these press reports were not all in very close proximity to the location of the accelerograph, the data do serve to indicate that the thresholds are in general agreement with the observations from the swarm: the first event, at 21:51 UTC on 1 March (PGV = 8 cm/s) did cause some damage in weak adobe buildings and alarmed the population; the events on 16 March (maximum PGV = 2 cm/s) were strongly felt and led to the suspension of classes at local schools; the strongest shock, on 17 March (PGV = 20 cm/s), caused appreciable damage. However, although this information provided an adequate basis for confirming the thresholds of PGV, there is insufficient data to calibrate the decay of these thresholds with the accumulation of duration or Arias intensity. An alternative approach was therefore required in order to take account in some manner of the number of perceptible events.

The approach adopted is based on the recurrence relationship for the induced seismicity. In order to allow the traffic light system to be based around the familiar Guthenberg-Richter frequency-magnitude plot, equivalent magnitudes were defined using the attenuation equation for PGV. The PGV-equivalent magnitude, M_{equiv}, for a given reference hypocentral depth of 2 km is defined to be the event magnitude required for an event at that range to produce the same surface PGV, according to the attenuation equation. With the above attenuation equation, the PGV-equivalent magnitude for an event with focal depth, h, is calculated as follows:

$$M_{equiv} = M + 2.0307\left[\log\left(\frac{2}{h}\right)\right] \quad (2)$$

It was assumed that the maximum ground motion due to an event would be expected directly above that event. Values of the ground elevation (with respect to mean sea level) directly above the hypocentre were drawn from a gridded digital elevation model (obtained from InSAR data). Having obtained in this way an equivalent magnitude referenced to the approximate depth at which the induced seismicity was expected to occur, thresholds in PGV-equivalent magnitude were calculated from the PGV thresholds determined previously (Figure 6).

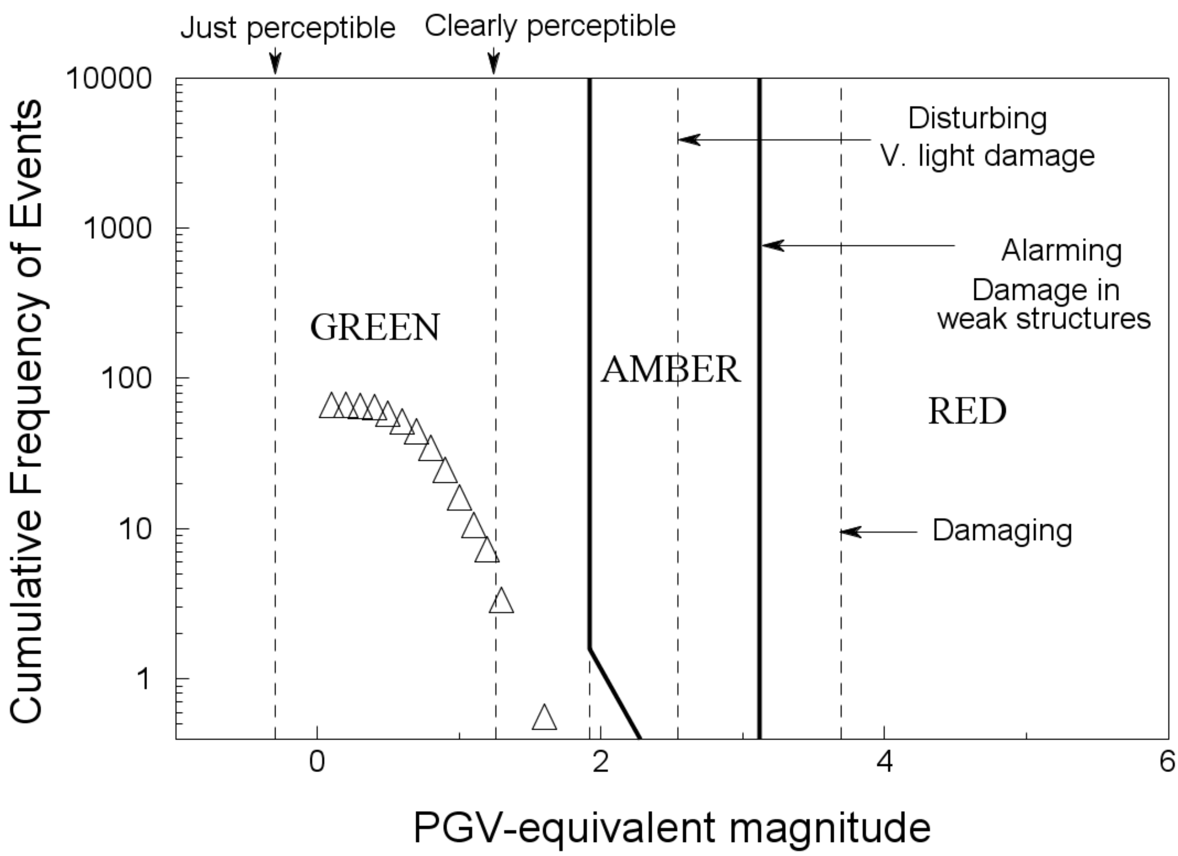

Figure 6. “Traffic light” boundaries superimposed on recurrence defined in terms of magnitudes adjusted to produce the same epicentral PGV if their focal depth was exactly 2 km. The triangles represent the cumulative recurrence data from the three episodes of pumping (totalling 54 days of pumping) normalized to a period of 30 days

The ISS seismic monitoring system deployed around TR8A (see Section 4.1) allowed real time monitoring and processing of the recorded seismicity so that the “traffic light” program could be executed automatically at specified time intervals, reading the event catalogue for a specified number of days up to the time of execution. For each event, M_{equiv} was calculated using Eq.(2). A Gutenberg-Richter type plot of $\log_{10}[N(M_{equiv})]$

against M_{equiv} was constructed for the data read and plotted in a window on the monitoring system's computer with the green and red thresholds displayed to allow a rapid assessment of the pumping operation's ongoing environmental compliance (Figure 6). The sloping part of the boundary between the Green and Amber zones reflects the recurrence data for a 30-day period for the background seismicity prior to the initiation of the HFR project. The rationale behind this boundary was that if the induced activity did not exceed the natural levels of micro-seismicity, there would be no problem with continuation of the hydraulic stimulations.

The boundaries on the “traffic light” were then interpreted as follows in terms of guiding decisions regarding the pumping operations:

- **Red** The lower magnitude bound of the Red zone is the level of ground shaking at which damage to buildings in the area is expected to set in.

- **Amber** The Orange zone was defined by ground motion levels at which people would be aware of the seismic activity associated with the hydraulic stimulation but damage would be unlikely.

- **Green** The Green zone was defined by levels of ground motion which are either below the threshold of general detectability or, at higher ground motion levels, at occurrence rates which are lower than the already established background activity level in the area.

4. OPERATION of the ‘TRAFFIC LIGHT’ for the BERLÍN HFR PROJECT

The system described in the previous section was tested during three periods of injection, which provided an opportunity to review, assess and calibrate the model. Movement of the seismicity into the amber zone was to be a signal for caution or possible reduction of the injection pump rate, and movement into the red zone was to be the signal to shut down the pumps.

4.1 Seismic Monitoring Networks

The monitoring of the HFR project involved two separate instrumental arrays. A seismograph network was installed around the geothermal field with the primary purpose of detecting micro-seismic activity as a means of monitoring fracture propagation. However, the seismograph monitoring system also permitted almost real-time calculation of hypocentres and magnitudes, from which median estimates of PGV at the surface could be obtained. A small network of strong-motion accelerographs was also installed at key locations in order to provide instrumental verification of the actual PGV levels.

Following a design study to determine the array configuration which would optimize the accuracy with which events in the region of interest could be located (following procedures similar to those described by Gibowicz and Kijko, 1994), the final decision to install a network comprising six monitoring sites centered on the injector well TR8A (Figure 7) linked to a central data gathering site by radio telemetry was taken. At five of the monitoring sites - TR1, TR12, TR14, Camp and Santa Anita - new shallow boreholes were drilled for the deployment of the sensors. At the sixth site sensors were deployed in an existing unproductive geothermal well. Two geophone packages were specified in each borehole, one shallow (~10 m) and one deep (~ 100 m). This provided additional redundancy in the system and resulted in the use of two distinct types of sensors – low frequency (4.5 Hz) fixed (ie. not gimbal-mounted) geophones in the shallower section of the wells and higher frequency (30 Hz) gimbaled geophones with magnetic orientation sensors for use at the bottom of the well – giving a broader frequency bandwidth coverage for the network as a whole. The objective in using shallow wells was to deploy the deep geophone units in the first known competent layer below the softer more discontinuous near surface while staying away from the known hot aquifers which would threaten the longevity of the equipment.

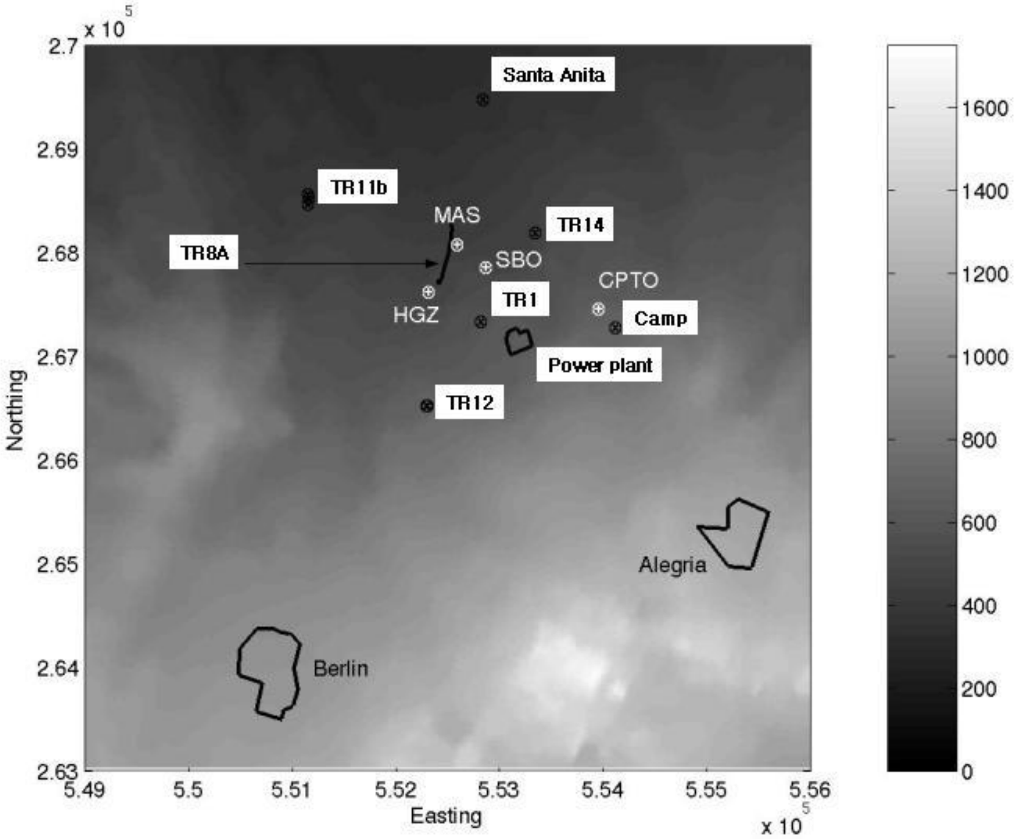

Figure 7. Map of the Berlín geothmermal field and surrounding area showing the location of the seismographs (black symbols) and accelerographs (white symbols). The gray scale indicates the ground elevation (in metres) with respect to sea level; the Eastings and Northings are given in metres.

The system started to acquire data on 30 October 2002. The period of background monitoring before the start of stimulation operations provided the opportunity to tune the system parameters to optimize the performance of the system to trigger and record as many genuine local events as possible. The dedicated micro-seismic monitoring network installed for the purposes of the Berlin HFR project, was designed to monitor the geothermal field area and the targeted injection well, TR8A, in particular more closely than the existing surface seismic network, BSSN. As such, the new network's ability to resolve detailed structures around TR8A through more precise event locations is greater while its coverage of the wider area is relatively poor when compared with the BSSN network. The HFR network's catalogue for the period prior to the initial stimulation of TR8A, that is from 30 October 2002 to 28 June 2003, contains 239 locatable events in the field area (Figure 8). Outside the periods of hydraulic stimulation, the background seismicity seems to be dominated by activity on and around a pair of active faults beneath the field.

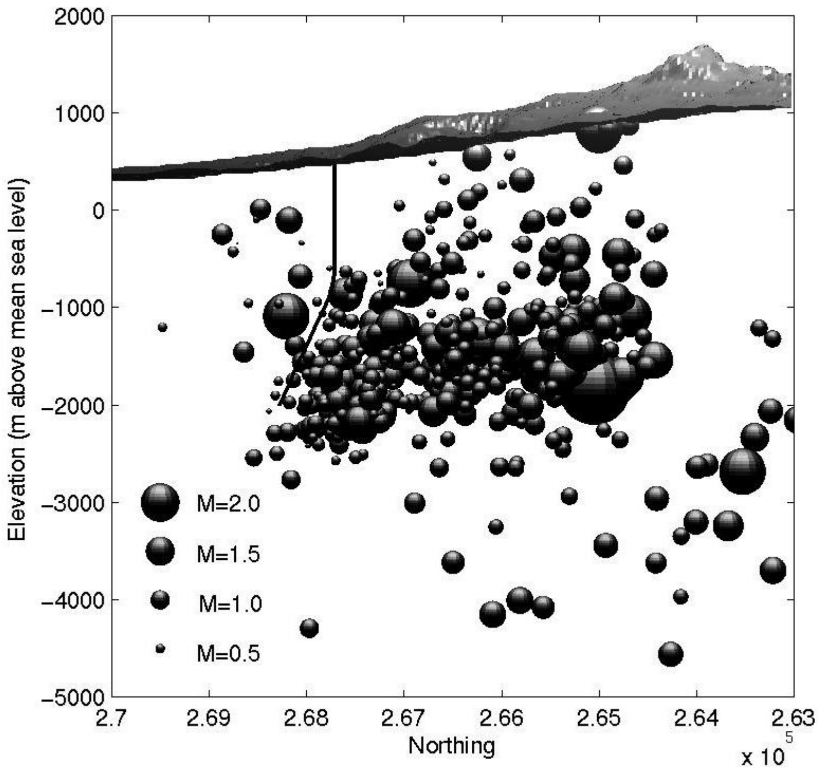

Figure 8. Cross-section of the seismicity at the Berlín field as recorded by the micro-seismic network during the entire period of fracture stimulation, including the intervals between periods of injection. Northing coordinates are given in meters. The black line shows the TR8A injection well. The largest event (265000N, elevation -2000) is the earthquake of 16 September 2003 (see Section 4.2)

The purpose of the strong-motion network was to provide PGV values for the “traffic light” system and to have independent verification of the system. It was decided to install digital accelerographs instead of velocity recorders in order to avoid the problems associated with obtaining acceleration time-series by differentiating velocity records. Furthermore, the calculation of the “traffic light” system parameters is straightforward from accelerographs. The instruments selected for the monitoring were three Etna models manufactured by Kinemetrics. These instruments have a triaxial recording capacity in the vertical and two orthogonal directions for a complete description of ground motion. The sensors provide an 18-bit resolution with 108 dB dynamic range and with variable trigger levels.

The main criteria for the installation of the accelerographs were location and security. The stations were located as close as possible to the expected fracturing zone, since it is where the strongest motions would be expected to occur. Another important aspect related to this criterion is the location of the instruments close to the exposed infrastructure in the communities enclosed by and in the immediate surroundings of the zone of expected fracturing. Regarding security, which was an important consideration, the stations were located inside existing and occupied buildings and the owners committed to maintain secure conditions. After visiting the area of monitoring, seven locations were initially selected and their conveniences in terms of location and security were compared. Finally, the following three locations were selected (Figure 7): MAS is a school in the La Montañita community towards the northwest end of the fracture zone. This same instrument had been operating during February and early March 2003 in a provisional location at the geothermal field (*Campamento*, CPTO). SBO is the house of Señor Santana Bonilla located about 400 m north of TR-1. In the *milpa* (maize field) adjacent to this adobe dwelling is a former LaGeo seismograph site. The instrument was located inside the concrete shelter of the former seismograph station. In this case, due to the lack of electrical supply, the instrument was powered on external batteries only. HGZ is the house of Señor Humberto González; it is located near to TR8A. The instruments of the Berlín Strong-Motion Network (BSMN) started operating in March 2003.

4.2 Seismicity during HFR operations

The Berlín HFR experiment comprised three periods of hydraulic injection in TR8A. The first of these was an attempt to hydraulically stimulate the formation along the open-hole interval below the casing. The objective of the second period of injection was to better characterize the shallow reservoir formation accessed below the casing shoe before going on to work the well over in preparation for a third phase of hydraulic stimulation of the deeper reservoir interval.

McGarr (1976) has argued and demonstrated that total seismic moment release shows a direct proportionality to the total volume injected in an experiment such as this, much as total moment release is seen to vary approximately linearly with volume of rock extracted in mining seismicity examples. A clear proviso here is that injection rates must of course be above the threshold at which non-fracturing leak-off processes through the rock matrix are able to account for all fluid injected. Hydraulic injections at the Soultz Hot Dry Rock geothermal site can be seen as an archetype for this kind of behaviour with very high detected event rates correlating precisely with the onset of pumping into the deep granite (Weidler *et al*., 2002).

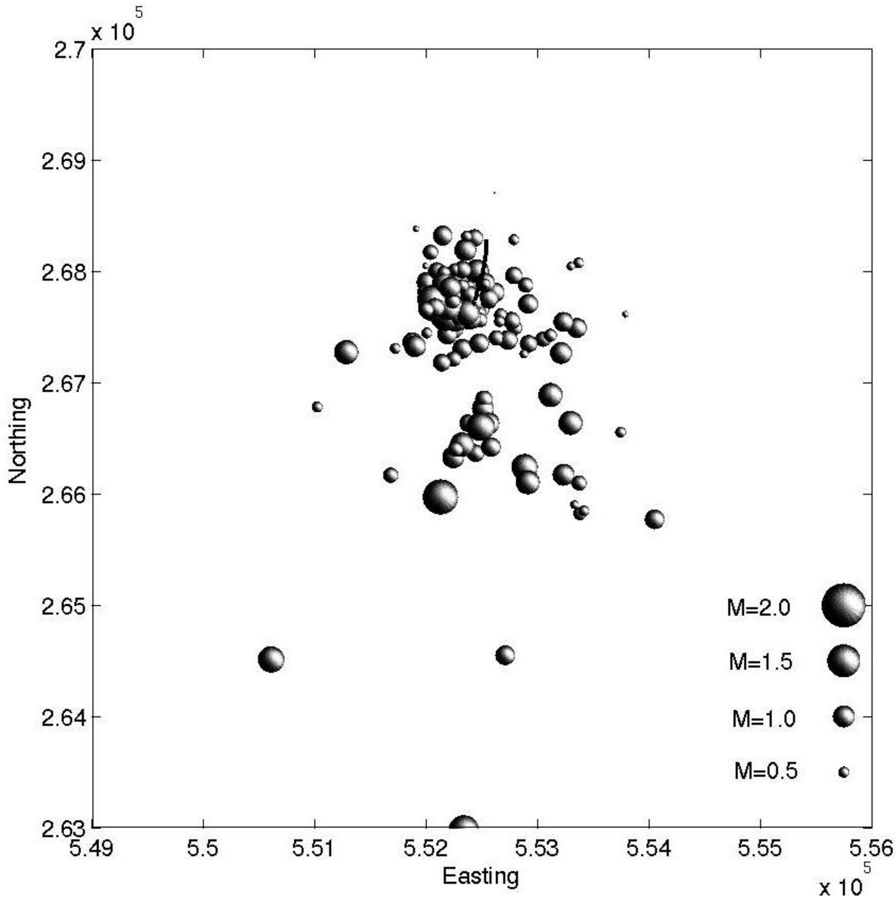

Figure 9. Epicentral map of seismic events during the fracture stimulation period (coordinates are expressed in meters). The black line is the projection of the TR8A injection well.

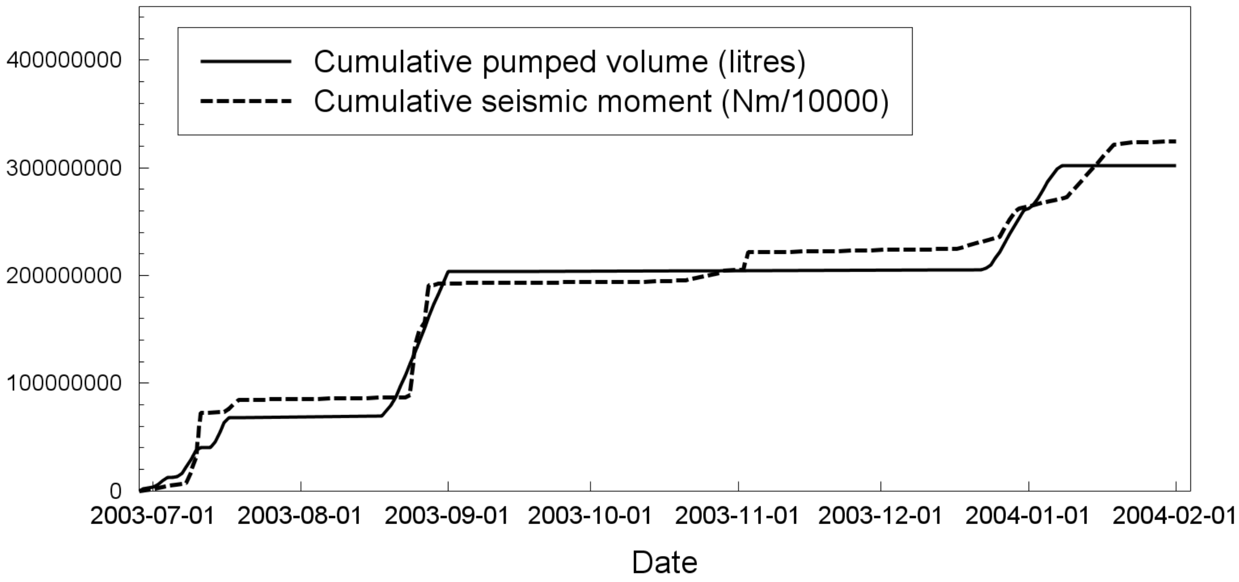

Figure 10. Comparison of cumulative volume of pumped liquid (litres) and induced seismicity (in terms of cumulative seismic moment). The seismicity occurred in the area bounded by coordinates 267000-268800 N and 551000-554000 E.

Preliminary analysis of the seismicity and injection rates in the Berlín field showed an approximate doubling of the seismic event rate during periods of pumping but a much less convincing correlation was observed than in the Soultz case. However, this reflected the conservative decision to consider a large area of interest for the “traffic light” calculations because of possible ambiguity regarding the cause of seismic events in the geothermal field in general. Closer inspection of the seismicity revealed two distinct zones of activity, one in the general area of the producing geothermal field and another, which only became notably active during pumping operations, directly around TR8A (Figure 9). Figure 10 shows the cumulative seismic moment release from this cluster of seismicity plotted together with the cumulative pumped volume for the three periods of injections between July 2003 and January 2004; the correlation between the two quantities is remarkable, leaving little doubt that that this seismic activity was induced directly by the fluid injection aimed at rock fracture stimulation.

The strongest recorded motion was produced by a 4.4 M_L event on 16 September 2003, with an origin time 07:20:08.6 (local time), during an interval between pumping episodes (Figure 10). The hypocentral coordinates, in local coordinates, 552724.7 (easting), 265051.1 (northing), 1834.9 m (elevation below mean sea level), were determined from the micro-seismic array. The magnitude was calculated by SNET using 24 stations (both seismic and accelerographic stations). The focal mechanism, also determined by SNET, is well constrained with a preferred fault plane solution with the following parameters: strike 106°, dip 71.3°, and rake 156.1°. The solution corresponds to a nearly east-west right-lateral strike-slip rupture.

An important question that arises is whether this event, which occurred 2 weeks after shut-in of the second period of injection, could have been triggered by the pumping operations. Of relevance in this respect is the observation that in some other reported cases of injection-induced seismicity the largest triggered events have been observed after the shut-in of pumping operations, the most well known and best documented example of this being the Rocky Mountain Arsenal episode (e.g. Hoover and Dietrich, 1969; Hsieh and Bredehoft, 1981). On the other hand, the location of the event almost 3 km to the south of TR8A, placing it on the other side of the geothermal field's production zone and with no sequence of smaller events linking it to TR8A, may argue against any direct link. Moreover, the geothermal fluids exhausted from the power plant are routinely re-injected under gravity feed into a number of wells in the vicinity of TR8A, with the objective of maintaining reservoir pressure. The fluid injected under high pressure for the hydraulic stimulation of TR8A described here was taken from this overall waste fluid budget such that the total volumes injected were unchanged from the levels sustained during normal field operation.

4.3 Revision of PGV Prediction Equation

During the monitoring period, the total number of records of local events obtained by the BSMN was 48; the trigger and de-trigger thresholds had been set to 0.0005*g* in the horizontal components and 0.001*g* in the vertical direction. Between 5 March and 6 September 2003, 16 records were produced. The earthquake swarm that started on 16 September with the 4.4 M_L event (the strongest in the series) accounted for the remaining 32 records retrieved from the three instruments in the network. Maximum and minimum PGV were 16 cm/s and 0.0011 cm/s, respectively, both recorded at the MAS station and associated with corresponding events of 4.4 and 0.3 M_L during the 16 September 2003 swarm.

The early recordings from BSMN indicated that Eq.(1) was consistently overestimating PGV, which suggested that site conditions in the Berlín geothermal field area are considerably stiffer than most of the sites contributing to the derivation of this equation, the majority of which lie, like much of El Salvador, on pyroclastic ash deposits. For example, predicted PGV for the largest 4.4 M_L event indicates an over-prediction of about 20%, and in other cases the differences can be as large as one order of magnitude.

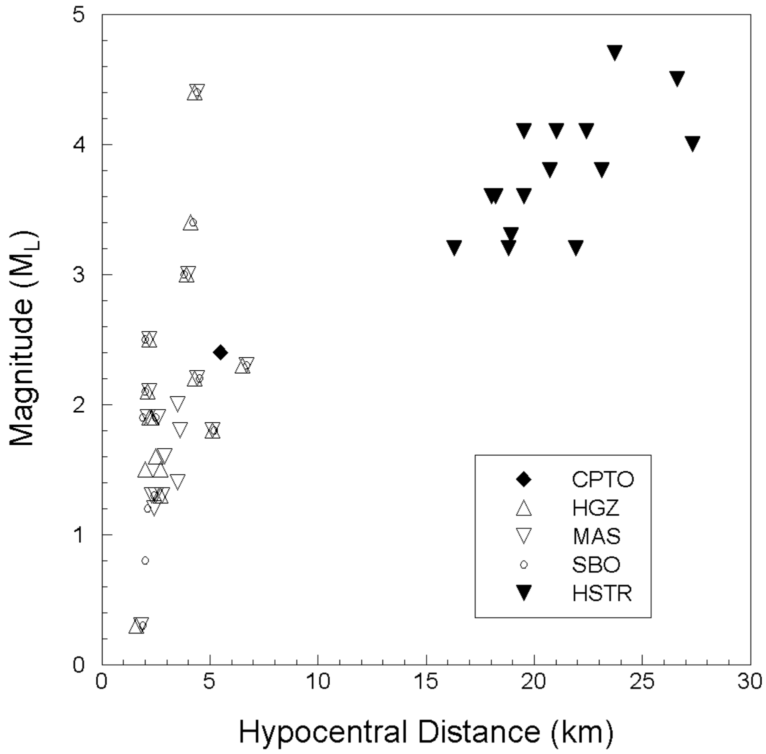

Figure 11. Magnitude-distance distribution of Berlín field and HSTR recordings.

A closer look at the swarm catalogue (Fig. 5) suggests that records from the HSTR station, the accelerograph in Zacatecoluca that provided many of the swarm records (see Section 3.5) appeared to have also been over-predicted by Eq.(1), and therefore it was decided to update the attenuation equation by combining data from HSTR station with the accelerograph data from BSMN. The rationale for this combination is that the HSTR station is located on stiff ground and therefore likely to be comparable to the site conditions at the BSMN stations. The magnitude-distance distribution for the dataset is presented in Figure 11.

The result of the adjustment to the combination of HSTR and BSMN data yields:

$$\log(PGV) = -2.701 + 1.022M - 1.058.\log(R) \quad (3)$$

With all terms defined as for Eq.(1) in Section 3.5. The logarithmic standard deviation on this new equation is 0.287, slightly less than that in Eq.(1).

4.4 Review of Pre-Defined Thresholds

All three stations recorded the M_L 4.4 16 September event at hypocentral distances of 3.6 km (SBO), 3.9 km (MAS) and 3.5 km (HGZ). The largest ground motion parameters were obtained at MAS station: 807.5 and 670.7cm/s^2 in the two horizontal directions, with the larger PGV value close to 16 cm/s. Figure 12 shows the acceleration and velocity time-series of the E-W component of the recording, which have a very short duration, consistent with the small magnitude of the event. Eq.(3) predicts a value of PGV of 14.8 cm/s at MAS, which is in good agreement with the recorded value.

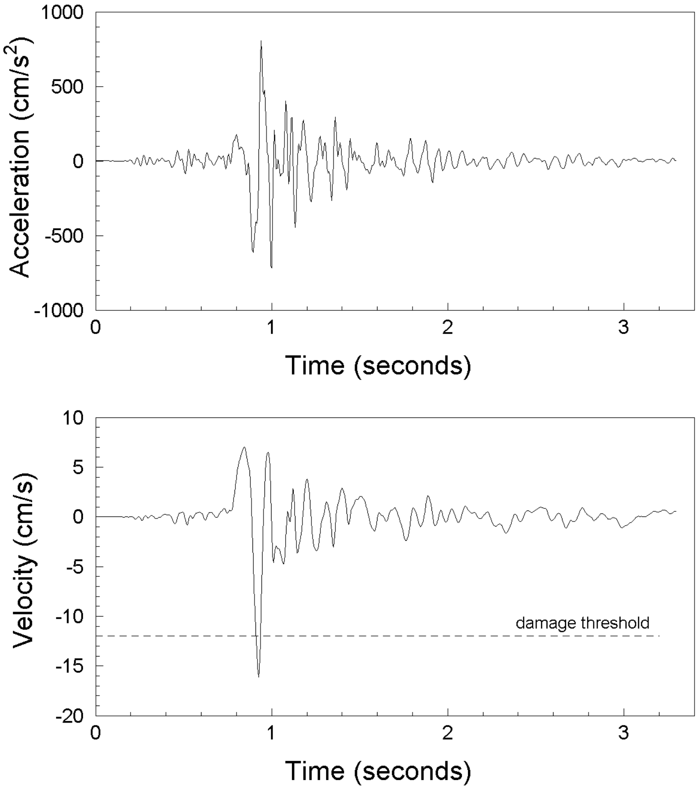

Figure 12. Acceleration and velocity time-histories from MAS recorded on 16 September 2003

The 5%-damped acceleration response spectrum of this component of motion has a peak just above 2*g* at a period just below 0.1 s, which vindicates the selection of this dominant period of the ground motions in interpreting frequency-dependent thresholds for permissible levels of vibration (Section 3.4).

Despite the large amplitudes of motion recorded at the MAS station during this event, there were no reports of any damage resulting from the event, even though, as indicated in Fig. 12, the PGV value did exceed the threshold specified for damage. This could raise doubts as to whether the thresholds were correctly defined, but consideration of this question needs to take account of the fact that the threshold of 12 cm/s was defined as a necessary, but not necessarily sufficient, condition for structural damage. The MAS station is a reinforced masonry (*mixto*) structure, with much greater seismic resistance than the adobe and bahareque houses that dominate the local area and would be unlikely to experience damage with ground motions below 20 cm/s. The maximum values of PGV at the other stations were 6.3 cm/s at SBO and 9.0 cm/s at HGZ. The shaking was of very short duration, as can be seen in Fig. 12, with a single cycle of high amplitude shaking, hence even if the motion did exceed strength levels in the exposed buildings little damage would be accumulated since there were no subsequent strong cycles to subject the buildings to permanent inelastic deformations.

The fact that the thresholds were marginally exceeded without damage occurring does not invalidate the thresholds since these were defined to provide a safe margin against adverse consequences amongst the local population. In the correlations between PGV and MMI of Wald *et al*. (1999), which were a major influence on the defined thresholds, the adopted values of PGV for each degree of intensity were from the lower fractiles of the scatter, whereas in reality these probably corresponded in many cases to recordings of larger magnitude earthquakes, where the low amplitude was compensated by longer duration. The use of these lower estimates of PGV for the very small magnitude earthquakes expected due to the HFR operations was a conservative decision taken in light of the over-riding need to ensure that no damage or injury was inflicted. A potential danger with such an approach could be that the levels are defined in such a conservative fashion as to lead to unnecessary interruption of the pumping operations; however, in the case of the Berlín project, over-riding importance was given to preventing of adverse effects on the local population and hence the possibility of premature suspension of pumping was a design consideration for the “traffic light”.

5. DISCUSSION and CONCLUSIONS

The seismic hazard presented by ground shaking due to small magnitude earthquakes induced by anthropogenic activities presents a very different problem from the usual considerations of seismic hazard for the engineering design of new structures. On the one hand, the levels of hazard that can be important, particularly in an environment such as rural El Salvador where very vulnerable buildings are encountered, are below the levels that would normally be considered of relevance to engineering design. Indeed, in probabilistic seismic hazard analysis (PSHA) for engineering purposes, it is common practice to specify a lower bound of magnitude 5, on the basis that smaller events are not likely to be of engineering significance (e.g. Bommer *et al*., 2001). On the other hand, unlike the hazard associated with natural seismicity, there is the possibility to actually control, to some degree, the induced hazard by reducing or terminating the activity generating the small events.

Although the problem of induced hazard is widely encountered in activities such as gas and oil extraction, waste disposal through injection, and geothermal energy production, there is very little published in the open literature regarding acceptable thresholds of motion and guidelines on how the hazard can be quantified, monitored and controlled. This paper, and the companion paper by van Eck *et al*. (2005), attempt to fill this gap by describing two different approaches to the problem that have been successfully implemented in two different environments. This paper has described the development of a “traffic light” for monitoring and controlling induced seismic hazard for a hot fractured rock geothermal project in Central America, a region of very high seismic hazard due to frequent natural earthquakes. The bases of the “traffic light” are thresholds for human disturbance and for damage to vulnerable houses defined in terms of peak ground velocity (PGV), with the thresholds inferred from recommendations for tolerable vibration levels due to blasting and pile driving, and from correlations between PGV and macro-seismic intensity. The thresholds are converted, via locally derived attenuation equations, into equivalent magnitudes for events occurring at a depth of 2 km, which is where the induced seismicity was expected. The basis for the “traffic light” in terms of frequency of events was defined by a recurrence relationship. The system was implemented in almost real time through the deployment of an array of sensitive seismographs around the fracture stimulation well, allowing rapid determination of hypocentral locations and magnitude. A small number of accelerographs were also installed to enable measurement of the induced ground motions.

The “traffic light” was tested during three periods of hydraulic facture stimulation in the Berlín geothermal field and found to be a useful and effective tool. The observed induced seismicity rates were, however, much lower than had been expected on the basis of experience in other similar projects and the “traffic light” system never showed anything other than a green light indicating good environmental compliance; the induced seismicity did not test the system to its full. The recordings of ground motions were found to indicate that the original attenuation equations employed, derived from recordings of small magnitude earthquakes in El Salvador, were over-predicting the induced motions and these were then modified using the recordings obtained from the geothermal field.

The authors of this paper believe it is important to record and disseminate field experiences in the definition, monitoring, management and verification of the hazard presented by induced seismicity, in order to build up a knowledge database that can lead to better practice. It is hoped that the ideas and results from the Berlín HFR project presented herein will be useful to others dealing with similar issues and also that this will encourage others to publish their own experiences.

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