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Contents

A Summary of Earthquakes in 2001

David Galloway and Bennett Simpson present a summary of seismic activity during 2001

Overseas

This year was not exceptional in terms of the number of worldwide earthquakes (Figure 1). There was 1 ‘great’ earthquake (magnitude over 8.0), 14 ‘major’ earthquakes (magnitudes between 7.0 and 7.9) and 130 ‘strong’ earthquakes (magnitudes between 6.0 and 6.9). These numbers are comparable with the long-term averages for these magnitude ranges, which are 1, 18 and 120, respectively. The number of people killed by earthquakes during 2001 was over 21,000 (Table 1), which is far greater than the long-term average of around 8,700.

The largest earthquake during the year, with a magnitude of 8.4 Mw, occurred on 23 June off the coast of Peru, approximately 190 km west of Arequipa and 600 km southeast of the Peruvian capital, Lima. It caused the deaths of over 81 people, including 26 killed by the subsequent tsunami, injured 2,734 more, left over 220,000 homeless and 64 are still reported as missing. An estimated 36,769 homes suffered some damage and a further 24,972 were completely destroyed. The coastal towns of Camana, Chala and La Punta in the Arequipa department suffered severe damage and some villages in the coastal area The most disastrous earthquake during the year, with a magnitude of 7.7 Mw, occurred on 26 January in the state of Gujurat, India. It caused the

Table 1 Earthquakes causing deaths in 2001

DATE	LATITUDE	LONGITUDE	MAGNITUDE	LOCATION	DEATHS
13 January	13.05 N	88.66 W	7.7 Mw	El Salvador	844
26 January	23.42 N	70.23 E	7.7 Mw	Southern India	20,023
13 February	13.67 N	88.94 W	6.6 Mw	El Salvador	315
17 February	13.79 N	89.11 W	4.1 Mb	El Salvador	1
23 February	29.51 N	101.13 E	5.6 Mw	Sichuan, China	3
24 March	34.08 N	132.53 E	6.8 Mw	Western Honshu, Japan	2
12 April	24.77 N	99.06 E	5.6 Mw	Yunnan, China	2
8 May	13.61 N	88.80 W	5.4 Ms	El Salvador	1
23 May	27.69 N	101.00 E	5.3 Ms	Sichuan, China	2
1 June	35.17 N	69.39 E	5.0 Mb	Afghanistan	4
23 June	16.27 S	73.64 W	8.4 Mw	Peru	81
7 July	17.54 S	72.08 W	7.6 Mw	Peru	1
17 July	46.74 N	11.20 E	5.0 Mb	Northern Italy	4
24 July	19.45 S	69.26 W	6.3 Mw	Northern Chile	1
9 August	14.26 S	72.68 W	5.8 Mw	Central Peru	4
27 October	26.32 N	100.65 E	5.7 Mw	Yunnan, China	1
4 December	15.33 S	72.52 W	5.8 Mw	Southern Peru	2
					21,291

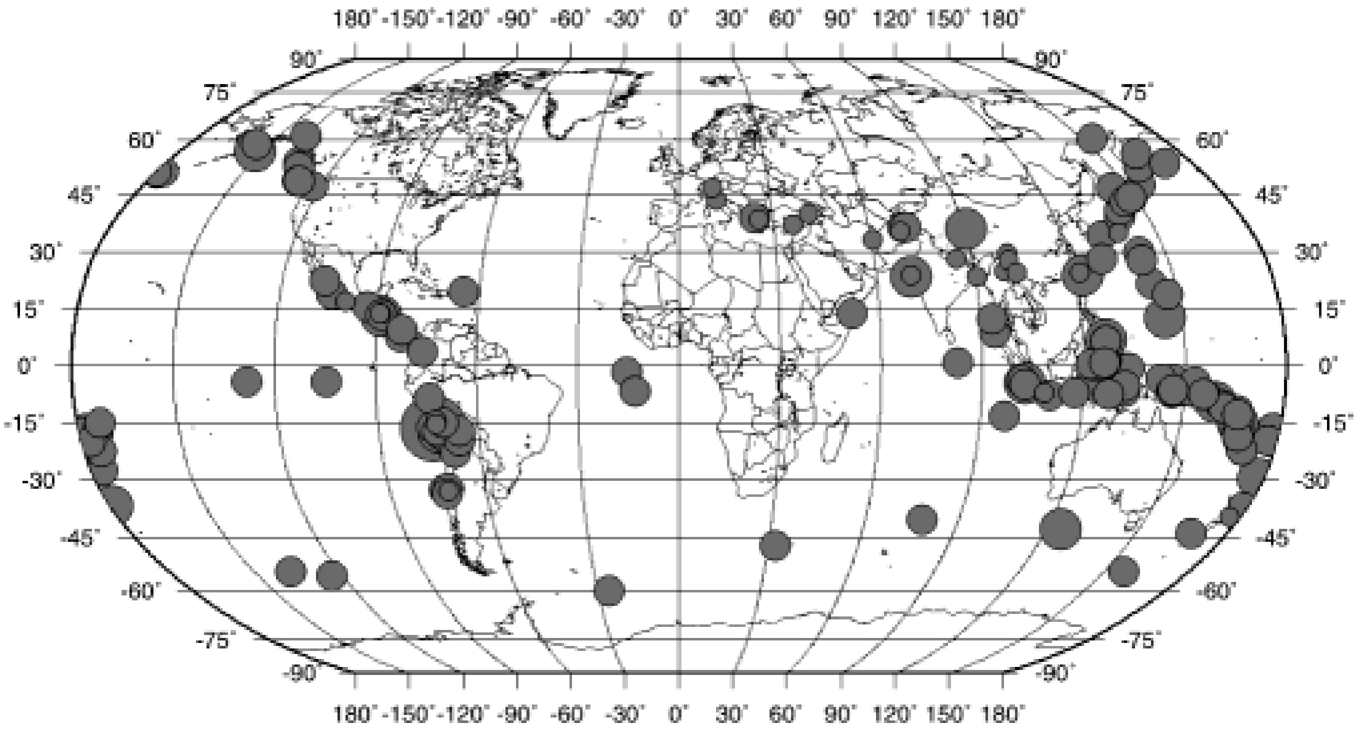
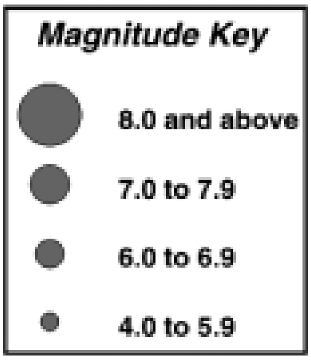


Figure 1 Notable world earthquakes of 2001



deaths of some 20,023 people (94% of the fatalities from earthquakes in 2001), injured over 166,800 more, left over 600,000 homeless and destroyed or damaged over 1,122,000 buildings affecting over 15 million people. The most affected areas were in the Gujurat districts of Bhuj, Kutch, Ahmadabad, Rajkot and Jamnagar area. There were significant effects on infrastructure with public facilities, including a number of schools and hospitals, power, water and telecommunication systems, bridges and roads being destroyed or damaged. Damage from the earthquake has been estimated at US$ 4.6 billion. The strain that caused this earthquake is due to the Indian plate pushing northward into the Eurasian plate. This northward crustal movement has also caused compression in the Gujarat area resulting in folds and thrust faults running approximately WNW-ESE. It was on one of these thrust faults that the earthquake occurred. This earthquake closely resembles the Rann of Kutch event of 16 June 1819 for which the exact death toll is not known but over 2,000 people were killed in Bhuj alone and some spectacular ground effects were caused including the 9 metre ‘Wall of God’ (the Allah Bund).

The year started off with a destructive earthquake (magnitude 7.7 Mw) in El Salvador, on 13 January. It killed 844 people, injured 4,723 more and completely or partially destroyed over 275,000 homes affecting over 1.3 million people (about one quarter of the population of El Salvador). The epicentre was in the Pacific Ocean, some 100 km southeast of the capital San Salvador. The earthquake caused major damage in the departments of San Miguel, Santa Ana, La Libertad, La Paz and San Salvador. The most affected area was Las Colinas where a landslide covered over 400 homes completely in mud. One month later, on February 13, an earthquake, with a magnitude of 6.6 Mw, occurred in the same general region with an epicentre approximately 30 km east of San Salvador. A further 315 people were killed, 3,399 more were injured and some 57,000 more houses were destroyed affecting over 250,000 people mainly in the San Vincente and La Paz departments. Both events were felt strongly throughout the region and as far away as Mexico City and Colombia. Two further people were killed, three more were injured and additional damage occurred in the epicentral area as the result of further earthquakes in the region on 17 February and 8 May. These earthquakes along with thousands of others form part of an ongoing sequence happening in the area. El Salvador sits on the western part of the Caribbean plate, where it is subducting the Cocos plate. Shallow intraplate (crustal) earthquakes occur within the crust of the overriding Caribbean plate, as in the February 13 event while deeper intraplate earthquakes occur within the subducting Cocos plate, as in the January 13 event. The damage, as a result of this sequence of earthquakes, has been estimated at US$ 3 billion.

On 28 February, an earthquake, with a magnitude of 6.8 Mw, occurred in Washington, USA. Over 400 people were injured and major damage occurred in the Seattle, Tacoma and Olympia areas. Several landslides were reported in the Tacoma area and liquefaction occurred in parts of Olympia and Seattle. The earthquake was felt from central Oregon to southern British Columbia and as far east as Montana.

Two fatal and damaging earthquakes occurred in Sichuan, China during 2001. The first, on 23 February with a magnitude of 5.6 Mw, killed 3 people, injured 109 more and destroyed or damaged over 60,000 homes in the Kanding and Yajiang Counties. The second event occurred on 23 May, with a magnitude of 5.3 Ms, killed 1 person and injured 566 others in the Ninglang County and killed 1 person and injured 39 others in the Yanyuan County. Eleven reservoirs, 4 power plants and 6 bridges were damaged as a result of these earthquakes.

In Western Honshu, Japan, on 24 March, an earthquake with a magnitude of 6.8 Mw, killed 2 people, injured 161 more and damaged or destroyed over 3,700 buildings in the Hiroshima area. Many water lines were broken and several railway tracks were damaged in the epicentral area. The earthquake was felt throughout western Japan from Kyoto to Kyushu and was also felt in South Korea.

On 12 April, an earthquake with a magnitude of 5.6 Mw, occurred in Yunnan, China. It killed 2 people, injured 190 more and destroyed or damaged over 30,000 homes in the Shidian area. On 27 October, a further, similar sized earthquake (magnitude 5.7 Mw) occurred in Yunnan and killed 1 person, injured 220 more and destroyed at least 3,400 buildings in the Yongsheng area. Yunnan Province is situated in southwest China to the east of the Tibetan Plateau and is one of the areas of China most prone to natural disasters.

In Afghanistan, on 1 June, an earthquake, with a magnitude of 5.0 Mb, killed 4 people, injured 20 more and destroyed several houses in the Parvan Province.
In Turkey, on 25 June, a magnitude 5.4 Mw earthquake injured 130 people and damaged 66 houses in the Osmaniye Province. Another magnitude 5.4 earthquake occurred in Turkey on 10 July and caused injury to 46 people and damaged 17 houses in the Erzurum region.

On 17 July, in northern Italy, 3 people were killed, from landslides, near Gargazzone and Val D'Ultimo and another died of a heart attack at Bolzano when a magnitude 5.0 Mb earthquake occurred in the region. Another 13 people were injured and minor damage occurred in the Merano area. The earthquake was felt throughout north eastern Italy, as far south as Venice and in parts of Austria, southern Germany, Slovenia and Switzerland.

One week later on 24 July, an earthquake, with a magnitude of 6.3 Mw, killed 1 person and caused injury to 3 more in Jaina, northern Chile. The epicentre was approximately 110 km east of the city of Iquique where minor damage and power, water and communication outages were reported. The earthquake also affected the cities of Arica, Pisagua and Putre.

On 26 July, over 100 houses and some older, historical buildings were damaged when a magnitude 6.5 Mw earthquake occurred in the Aegean Sea. Damage to the main water supply on Skyros, Greece was also reported.

In Bangladesh, on 19 December, a magnitude 6.8 Mw earthquake caused injury to over 80 people and caused severe damage to buildings in the old town of Dhaka.

Other notable world earthquakes during 2001 included; Jawa, Indonesia, on 28 June (magnitude 5.0 Mb) which injured several dozen people and caused damage to over 2,500 buildings in the Jawa Barat Province and Qinghai, China, on 14 November (magnitude 7.8 Mw) which caused damage in the Xidatan area.

UK Earthquakes

The British Geological Survey detected and located some 135 earthquakes in the British Isles and surrounding continental shelf areas during the year (Figure 2), with 37 of them having magnitudes of 2.0 ML or greater. Of these, 10 are known to have been felt, together with a further 6 smaller ones, bringing the total to 16 felt earthquakes in 2001.

The largest onshore earthquake, with a magnitude of 4.1 ML, occurred near Melton Mowbray, Leicestershire on 28 October. BGS initiated a macroseismic survey and earthquake questionnaires were distributed through local and national newspapers. Approximately 1,800 emailed responses were received, the most received for any UK earthquake so far, together with an estimated 4,200 paper questionnaires, giving a total of 6,000 responses in all. Many media interviews were conducted and a large number of enquiries were received. The earthquake was felt throughout Lincolnshire, Leicestershire, Warwickshire, Yorkshire, Shropshire and Nottinghamshire. The most distant reports were from the following places: in the west, the earthquake was felt near Chester, in the east, the earthquake was reported felt in King's Lynn, Norfolk, in the north, Knaresborough marked the limit of observation and in the south, the shock was felt as far as Oxford. There were reports of damage to chimneys in the Melton Mowbray area, indicating an intensity of 6 EMS. Felt reports described, "we ran into the streets", "the whole house shook", "the table moved" and "we were very frightened". A maximum acceleration of 0.02g was measured at the strong motion station at Keyworth, some 15 km from the earthquake. The focal mechanism for the Melton Mowbray earthquake also shows oblique normal faulting along either a near N-S fault plane dipping at 51° or along a near E-W fault plane dipping at 58°. The average maximum compressive stress direction has an azimuth of 140°and

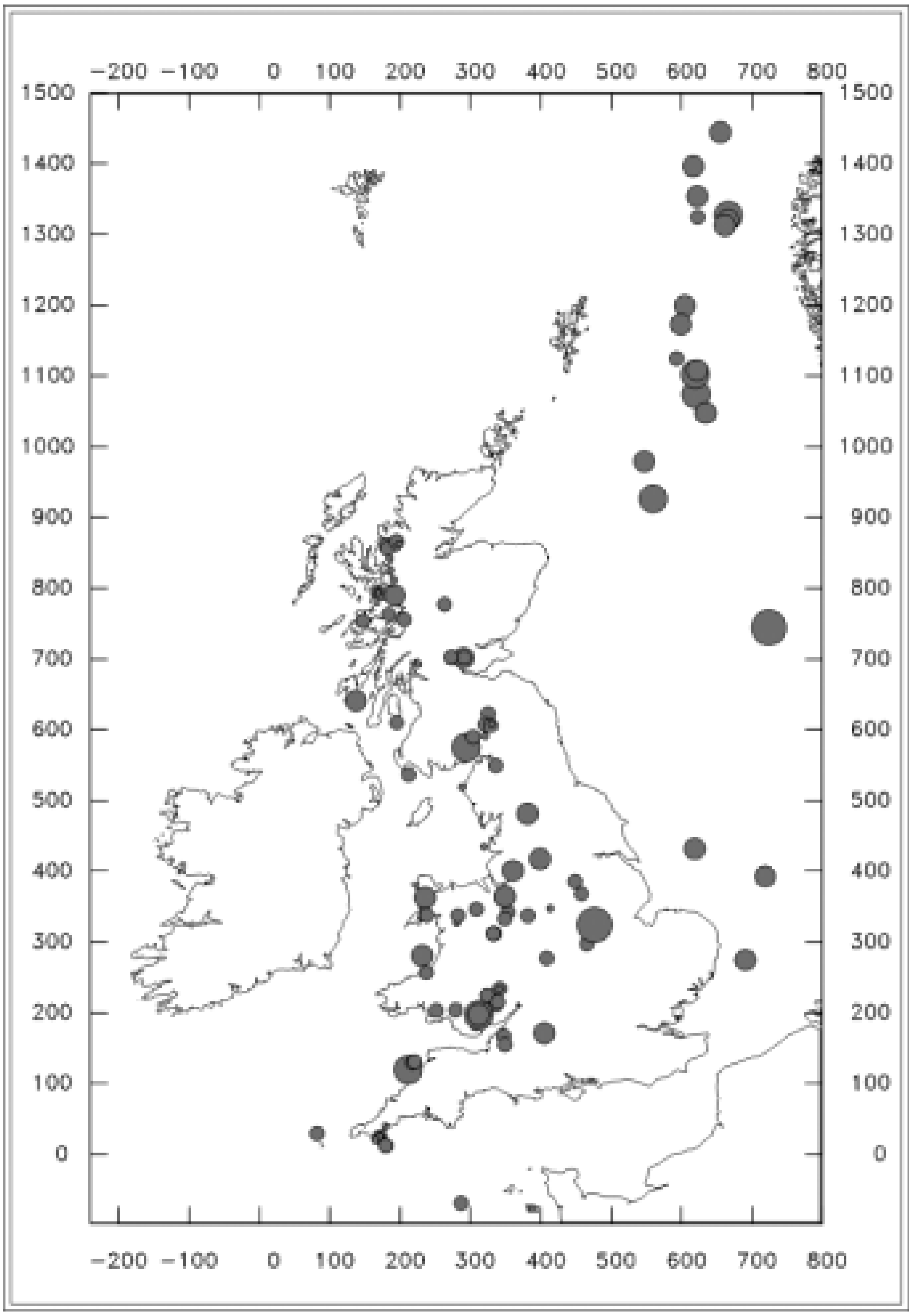
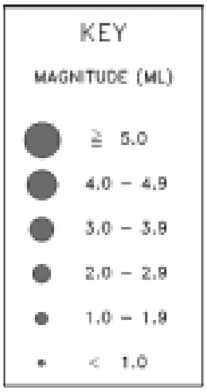


Figure 2. Epicentres of all UK earthquakes located in 2001 (from the Bulletin of British Earthquakes 2001)

dip of 55° and the minimum stress direction strikes at 44° and dips at 4°.

The largest offshore earthquake occurred in the Central North Sea on 7 May. It had a magnitude of 5.0 Mw and was located approximately 410 km east of Edinburgh. It was felt on three nearby oil platforms in the Ekofisk field, The Ekofisk Hotel platform control tower described, "a swaying lasting 2 minutes which left us feeling dizzy", they also confirmed that the Albuskjell platform some 15 km to the north and the Eldfisk platform, some 26 km to the south, reported similar felt effects. The focal mechanism obtained for the earthquake shows normal faulting with north-south trending nodal planes. A further 22 events occurred in the North Sea and surrounding waters during the year, with magnitudes ranging between 1.2 and 3.9 ML, and were located using both the BGS and Norwegian networks.

An earthquake with a magnitude 3.0 ML occurred on 13 May, with a location near Dumfries. BGS received many felt reports, from the Police, the media, Dumfries Council and residents of the Dumfries area. Felt reports described, "the entire house shook", "the neighbours felt a shaking and ran into their back gardens", "the floor moved" and "felt like an explosion". A macroseismic survey was conducted and over 590 replies were received, indicating a maximum intensity of 5 EMS. This event was followed by four aftershocks on the same day with magnitudes ranging between 0.5 and 1.3 ML, the largest event was felt with intensities of at least 3 EMS. The focal mechanism obtained for the Dumfries earthquake shows predominantly strike-slip faulting along near vertical fault planes striking approximately NNW-SSE and ENE-WSW respectively. The near horizontal, NW-SE orientation for the principal stress direction (P-axis) is in agreement with the expected regional stress tensor.



An earthquake, with a magnitude of 3.6 ML, occurred off Hartland Point, Devon, on 31 May. BGS received many felt reports from residents of Cornwall and Devon, who described, "I ran outside alarmed", " I thought a nuclear explosion had gone off" and "the whole house shook". A macroseismic survey was conducted and over 520 replies were received, indicating a maximum intensity of 5 EMS.

Near Mallaig, Highland an earthquake with a magnitude of 1.7 ML occurred on 20 June. Felt reports were received from the village of Mallaig, where intensities reached 3 EMS. Felt reports described, "I felt a shudder through my feet" and "sounded like a large explosion".

Fifteen events occurred in Constantine, Cornwall throughout June, with magnitudes ranging between 0.0 and 1.1 ML. This is an area that has experienced similar swarm activity in the past.

An earthquake with a magnitude of 2.2 ML occurred on 27 June, with a location near Sedbergh, Cumbria. A single felt report was received from a resident of Cowgill, some 9 km to the west of the epicentre, who described the following "the whole house shook, I was woken from sleep and I heard a bang", indicating an intensity of at least 4 EMS.

On 21 July, an earthquake with a magnitude of 1.9 ML occurred at the northern end of the Isle of Mull, western Scotland. BGS received one felt report from a resident of Salen, approximately 15 km southeast of the epicentre, who described "the whole house shook" and "quite a weak rumble", indicating an intensity of 3 EMS.

On 1 September, an earthquake with a magnitude of 1.8 ML occurred near Blackford, Tayside. BGS received felt reports from residents of Glendevon, which described, "the whole house shook". A further two earthquakes with magnitudes of 2.1 and 1.3 ML, occurred in the Blackford area, with intensities of 3 EMS, respectively, on 19 December. Felt reports were received from the Blackford and Glendevon areas of Tayside and described, "we heard a loud rumble", "the house shook" and "the radiators rattled". This is an area that has continued to be active in recent years; 49 events occurred in 1997, of which five were felt by local residents; 10 events occurred in 1998, of which 2 were felt by local residents, 3 events occurred in 1999 and 4 events occurred in 2000, of which 3 were felt. In the same general area in 1979, a magnitude 3.2 ML Ochil Hills earthquake was felt with a maximum intensity of 5 EMS.

An earthquake with a magnitude 3.1 ML occurred on 10 October, with a location near Bargoed, Mid-Glamorgan. BGS received felt reports from residents of the Bargoed area. Felt reports described, "the bed was shaking", "the entire house shook" and "I was woken from sleep". A macroseismic survey was conducted and approximately 120 replies were received, indicating a maximum intensity of 4 EMS. This event was followed by three aftershocks with magnitudes of 1.6, 1.6 and 2.5 ML; the largest event (2.5 ML) on 18 October was felt with intensities of 4 EMS. The Bargoed focal mechanism shows oblique normal faulting along either a NW-SE striking fault plane dipping at 38° or a NNE-SSW striking fault plane dipping at 63°. The average maximum compressive stress direction has an azimuth of 142°and dip of 61° and the minimum stress direction strikes at 258° and dips at 14°.

Near Swindon, Wiltshire, an earthquake with a magnitude of 2.7 ML occurred on 18 March. Earthquakes of this size are usually felt when they occur onshore but enquiries to local Police stations and post offices revealed that no felt reports were received. This is an area that has experienced little seismicity in both the historical and instrumental periods, with only one event located since 1970 within a 20 km radius of this event.

Near Chester, Cheshire, three events occurred on 17 October, with magnitudes of 2.4, 2.1 and 1.5 ML, BGS received no felt reports for these earthquakes.

An earthquake with a magnitude of 2.3 ML, occurred near Anglesey, Gwynedd on 5 November. BGS received a single felt report for this earthquake which described "a bang, then a rumbling" indicating an intensity of at least 2 EMS.

An earthquake with a magnitude of 1.5 ML, occurred on 1 December with a location near Ballachulish, Highland. BGS received a number of felt reports from residents of Glenachulish, Ballachulish and Onich. Felt reports described, "we heard a loud rumble", "we felt a vibration" and "we ran outside", indicating an intensity of 4 EMS.

On 16 December, an earthquake with a magnitude of 2.6 ML occurred approximately 6 km southwest of Halifax, West Yorkshire. BGS received felt reports from residents of Halifax and Todmorden which described, "we heard a loud rumble", the "whole house shook" and "we ran outside", indicating an intensity of 4 EMS. This event locates approximately 3 km southeast of the magnitude 4.0 ML Todmorden earthquake, on 7 March 1972, which was felt with intensities of 5 EMS.

In North Wales, two events on 6 and 11 December with magnitudes of 1.2 ML and 0.7 ML respectively, occurred on the Lleyn Peninsula, in the same area and at similar depths (20 km) as the magnitude 5.4 ML Lleyn earthquake of 19 July 1984, which was felt throughout England and Wales and into Scotland and Ireland.

The coalfield areas of Yorkshire, Staffordshire, Nottinghamshire and Derbyshire continued to experience shallow earthquake activity that is believed to be mining induced. Some 4 coalfield events, with magnitudes ranging between 0.8 and 1.8 ML, were detected during the year.

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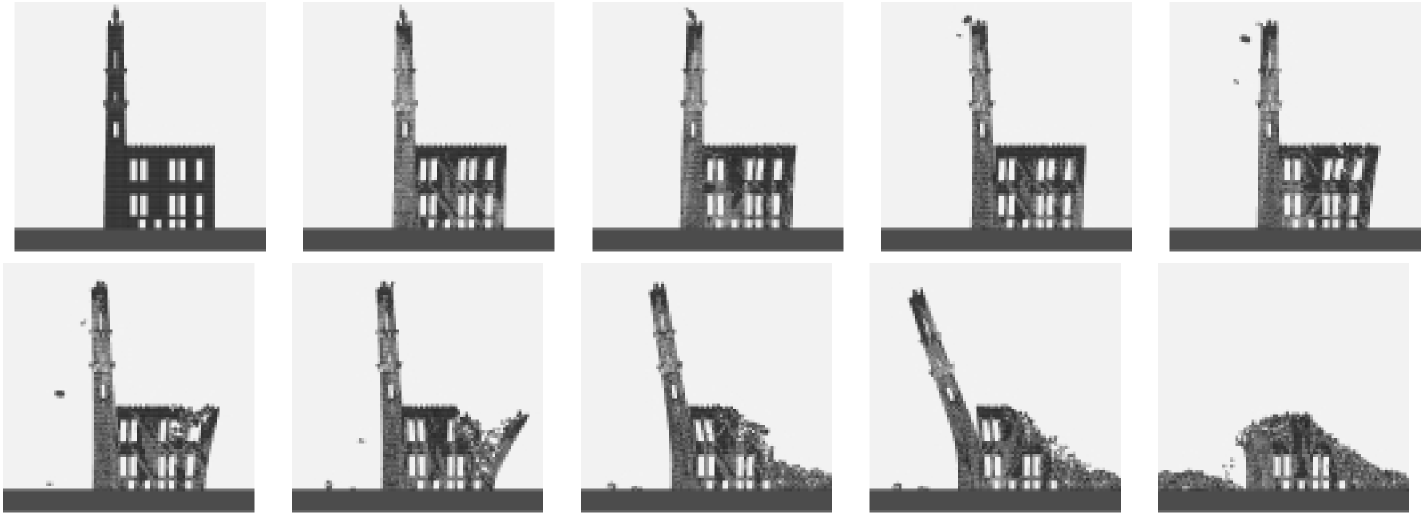
The 'Bulletin of British Earthquakes 2001' edited by B A Simpson and D D Galloway will be published in April 2002. Copies of this and previous years' bulletins can be obtained from the Earthquake, Forensic Seismology and Geomagnetism Group secretaries and from BGS bookshops. For further details contact: D D Galloway, Earthquake, Forensic Seismology and Geomagnetism Group, British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, Scotland, UK.

Numerical Modelling of Masonry to Predict Performance of Retrofitted Strengthening

Paper by **C L Brookes** of Gifford and Partners, UK



Collapse of a numerically simulated masonry building under strong ground movement

INTRODUCTION

The prediction of the behaviour of non-engineered historic masonry buildings under seismic loading remains a challenge. The use of continuum based numerical models to simulate discontinuous structures, such as masonry, is fraught with difficulty. The introduction of discontinuities such as cracks during the loading event, or as a result of loading history, has to be wholly or partly predetermined. The use of gap elements allows cracks to open and maintain normal and shear force connection when closed but the crack locations have to be known in advance. Another approach is to avoid explicit representation of discontinuities but instead smear their effect by using a brittle non-linear material model. However, these models fail to predict mechanisms where, for example, initially isolated parts react dynamically together. Continuum methods can give satisfactory results but generally fail to provide a practical method of analysis for masonry.

As an alternative to the traditional finite element continuum approach, a discrete element (DE) formulation has been employed to simulate masonry with and without strengthening. So far the results of the analyses have been applied to parts of buildings and used to help develop remedial design philosophies by providing simulations under specific ground excitations.

A separate project where the engineering analysis has also been based on the DE technique has involved the successful strengthening of nearly seventy masonry arches. Predictive verification of full-scale tests underlies this work and has involved calculated collapse loads of masonry arch bridges as well as supplementary load tests on in-service bridges. Results have been shown to correlate very closely with tests (Brookes, Tilly 1999).

As the technique is applied to Earthquake Engineering it is hoped that the performance of whole buildings can be checked in order to get an indication of likely performance with and without strengthening. Although by nature historic masonry is difficult to parameterise it is the authors firm belief that using suitable sensitivity analyses great benefit can be achieved by numerical simulation.

ANALYTICAL REQUIREMENTS

In order to represent masonry with or without retrofitted reinforcement, particularly in seismic engineering where non-linear structural performance defines how ductility and energy absorption characteristics are exhibited, the following types of fundamental behaviour need to be included in the model.

i) Material and geometric properties of the masonry blocks themselves.

ii) Contact-gap-friction effects along joints between the masonry blocks.

iii) Depending on block and joint properties, the ability to evolve further joints by fracturing which in turn depends on limiting tensile strength and fracture energy.

iv) Full account of stiffness and derived inertia loads which may occur over very short time intervals.

v) The capability to model post-failure behaviour to help verify simulations against the evidence collected after observed seismic damage and collapse.

vi) To allow stress and initial damage from previous seismic events to be included.

vii) The ability to represent retrofitted reinforcement including materially non-linear behaviour of the steel and the non-linear shear coupling behaviour of the bond with the surrounding masonry.

To date, most numerical simulations of masonry have been based on finite element continuum methods in which sophisticated and often-complex material models in conjunction with arrays of gap or interface elements are used to account for the requirements listed above. A more intrinsically satisfactory approach for masonry is to base the analysis on a series of *discrete elements.* This more natural approach can be used to represent ranges of masonry from completely intact buildings to piles of random rubble.

DISCRETE ELEMENT TECHNIQUE

The technique used to perform all the analysis in this study is the discrete element (DE) method. This is a development of the distinct element method (Cundall, 1971) in which the concept of individual elements being separate and reacting with their neighbours by contact through friction/adhesion was first successfully applied to geotechnical and granular flow problems. Here elements were considered rigid but later developments (Munjiza et al, 1995) included the addition of element deformations and fracturing, with some overlap with traditional finite element theory.
In the current investigation the DE formulation available in the explicit dynamic version of ELFEN (Rockfield Software Limited, 1998) has been used. Explicit solvers (solution of transient dynamic problems by central difference explicit time integration) are intrinsically dynamic and are well suited to the analysis of structures with discontinuous behaviour such as masonry. Equilibrium difficulties, often encountered with more traditional implicit solvers, are completely avoided although more reliance is required on verification.

The heart of the DE technique is concerned with automatic contact detection between facets of solid polygons (separate blocks). Tiered geometric search algorithms are used to provide short lists of potential contacts, rather than considering all those possible. More precise and computationally expensive calculations are then targeted at these short lists to identify actual contact potential. Finally, using the penalty method and defined interface properties (Coulomb friction is used in this study) facet tractions are resolved. The finite element method is applied to describe the behaviour of the polygon solid material. This process is repeated for each time step of the analysis.

Essentially two different approaches have been considered for the non-linear analysis of masonry each requiring different modelling approaches.

Macro Blocks. The category where the joints between blocks have predominantly no strength and models the construction generally found in historic structures.

Brittle Material. This is where the masonry blocks and joints have predominantly similar strengths, as is more likely in modern forms of construction or where masonry is weak and random.

Both of these approaches have been investigated for shear wall applications to investigate the sensitivity of seismic resistivity to mortar properties (Brookes, Mehrkar-Asl, 1998).

Macro block – Current Investigation
The macro block approach has been achieved by separately modelling each block or group of blocks in the structure and applying permanent static loads and seismic excitation to the base. Individual blocks of elements have defined elastic and plastic materials and are arranged to the required bond. All joints and therefore potential discontinuities are predefined and have friction parameters assigned. It is assumed that failure at joints always develops before blocks fail. However, the introduction of a von-Mises non-linear material model without hardening has been used to approximately represent block crushing thus giving a compressive stress cap. Material properties have been based on characteristic values determined for the masonry as a whole.

REINFORCEMENT REPRESENTATION

The finite element technique is used to model the reinforcement independently of the masonry using a partially constrained spar formulation (Roberts, 1999). Connection between the reinforcement and masonry models is achieved through non-linear bond elements. Modelling of reinforcement arrangements is completely automated without the need for topologically consistent element meshes thus accelerating the modelling process and permitting rapid comparison of designs.

SHEAR WALL INVESTIGATION

As part of the continuing development of Cintec anchor applications and the expansion of joint venture historic structure remedial projects Gifford and Partners with Cintec International Limited are undertaking limited studies to investigate how the seismic resistivity of low-rise non-engineered masonry buildings might be improved (Cintec International Limited, 2002).

Cintec anchors (retrofitted reinforcement) are comprised of stainless steel bar(s), a grouting sock and an engineered grout. Installation is by precisely drilled holes using wet or dry diamond coring technology. The sock consists of a specially woven polyester fabric shaped into a tubular sleeve to fit the required hole diameter. The sock controls the volume of grout used and ensures good contact is achieved with the surrounding masonry. Presstec grout is used having similar characteristics to Portland Cement based products, contains graded aggregates and other constituents which, when mixed with water, produce a pumpable grout that exhibits good strength with no shrinkage. The size of the steel anchor, strength of grout and diameter of hole can be varied to provide the required design parameters and to provide good stiffness compatibility with the masonry. Design parameters such as the bond strength between the grout and the masonry, which is often critical, are normally derived from static pullout tests.

To date effort has concentrated on the detailed analysis of masonry shear walls, the primary structural element in masonry buildings, it being recognised that the out of plane behaviour of masonry panels has been the subject of much previous work (Key, 1998).

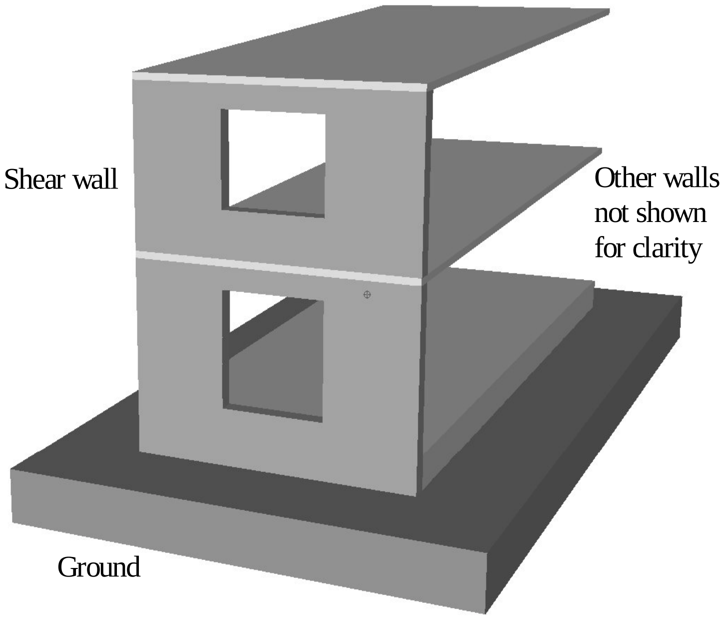


Figure 1. General arrangement of idealised building

These shear walls are described below. The main objectives of the analyses were to provide some comparison between the performance of the walls with and without strengthening and to continue to explore the potential of the DE technique including modelled reinforcement applied to masonry under dynamic loading.

An on-going programme of strengthening projects using the DE method to predict the ultimate strength of masonry arches, including comparisons with full scale tests, has shown the technique to be very accurate and better than alternative analyses for the case of static loading. Further work involving the out of plane prediction of masonry wall behaviour under high-speed dynamic loads arising from blast is also encouraging.

Description

The masonry shear wall under investigation is shown in Figure 1. The wall has shallow foundations over rock and has been considered with and without a large opening in each storey. It forms the shorter side of the rectangular building and supports two floors capable of behaving as diaphragms. The longer side walls (not explicitly modelled) partly support the floors, and have little out-of-plane shear resistance. Vertical body forces and imposed loads are supported uniformly by all of the external walls. Loads developed by horizontal seismic ground accelerations in the transverse direction of the building are resisted by in-plane forces in the side walls. One of these walls is the subject of the current investigation.

DE Model

Several plane stress DE models of a single side wall were developed incorporating the masonry blocks and slabs. The vertical loads and masses attributed to the slabs were modified to reflect mass and load transfer from the rest of the building. The wall is constructed from ashlar blocks, bedded on narrow and relatively weak mortar.

Although it is feasible to include all of the blocks in the macro block representation, previous work on masonry arches has shown that there is little advantage in terms of accuracy and computational efficiency. Hence, each block may in reality include several squared stones. The floor slabs and foundation were defined as separate continuums with similar perimeter frictional properties to the blocks. It has been assumed that the floors and foundation are constructed such that their global behaviour is linear elastic. For example strong reinforced concrete slabs.

Material Properties

Masonry material properties were based on those typical of well-built ashlar construction and using weak sandstone laid with a soft mortar. The strength and stiffness of the modelled blocks have been based on characteristic values for the masonry treated as a whole. The contact and frictional behaviour of the mortar is modelled explicitly at the joints.

Loading

Hypothetical horizontal seismic loading based on a circular frequency of approximately 0.6 Hz and containing six shocks was derived and applied to all of the models as displacement functions at foundation level. Two magnitudes of this simplified motion have been used with peak accelerations of 0.15g and 0.3g.

Vertical accelerations were not considered due to the inherent inconsistencies in the distribution of mass that were required to simplify the problem to one of two dimensions. Whilst concurrent vertical motion has an influence on the overall behaviour of masonry shear walls, it is generally accepted that horizontal motion is critical.

Strengthening

Both the plain wall and wall with openings were modified to include various arrangements of strengthening. Proposed dispositions of reinforcement included horizontal anchors through individual block courses, vertical anchors at the ends of the wall and diagonal anchors. Combinations of these patterns have also been considered.

The reinforcement is introduced into the wall using the Cintec anchor system. All dispositions of reinforcement investigated used single 20mm diameter ribbed bars installed in 50mm diameter holes. The anchors are designed not to be deliberately stressed but attract load during a seismic event. The modelled anchors permit recovery of bond stresses, axial stresses and slippage along the length of the anchor at any time during loading.

Figure 2 shows a typical model including DE boundaries (bold), finite element subdivisions (fine) and modelled reinforcement (bold).

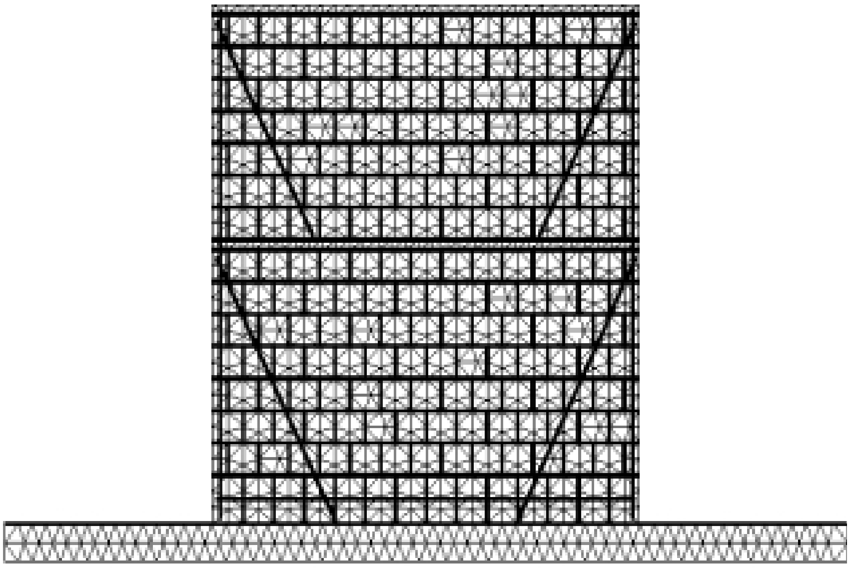


Figure 2. Typical wall DE and reinforcement model

DISCUSSION OF RESULTS

DE simulations were carried out to show how the strength and ductility of the walls varied with reinforcement arrangement. Where walls have exhibited a high degree of seismic resistivity an additional ground motion with peak accelerations of 0.3g have been applied.

Unstrengthened simulations
Figure 3 illustrates compressive stresses and deformed geometry half way through the seismic event and after ground motion has ceased. The shaded contours range between 2.2 N/mm^2 (dark, compression) and -0.2 N/mm^2.

It has been theoretically shown that the predicted ductility of the walls is highly sensitive to the properties of the joints and the duration of the event (Brookes, Mehrkar-Asl, 1998). Furthermore, the inherited damage history from preceding shocks increases the seismic vulnerability of the wall. Here the influence of openings is also considered with the aim of developing an arrangement of reinforcement that works equally well for plain walls as well as those with openings.

Figure 3 shows that after the 0.15g events the plain wall remains relatively undamaged with cracking in both storeys. Sudden stress discontinuities as well as the relative movement of blocks mark cracking. Cracking in the second storey results in significant dilation across the wall. It is less in the first storey and is associated more with locked in stresses. Doubling the acceleration results in massive damage. With much less masonry capable of resisting shear, the wall with openings is severely damaged after three shocks and collapses.

The results show the general behaviour as well as movement and the initiation of cracking. This movement develops rapidly into local failure mechanisms when subjected to continued shocks. The predicted failure and local collapse is similar to damage frequently sustained in seismic regions. Hence, these three models have been used as the benchmarks to compare the performance of various retrofitted reinforcement schemes.

Strengthened simulations
Nine reinforcement arrangements were investigated and most resulted in more damage than the unstrengthened case.

Results obtained from schemes exhibiting minimal damage are shown

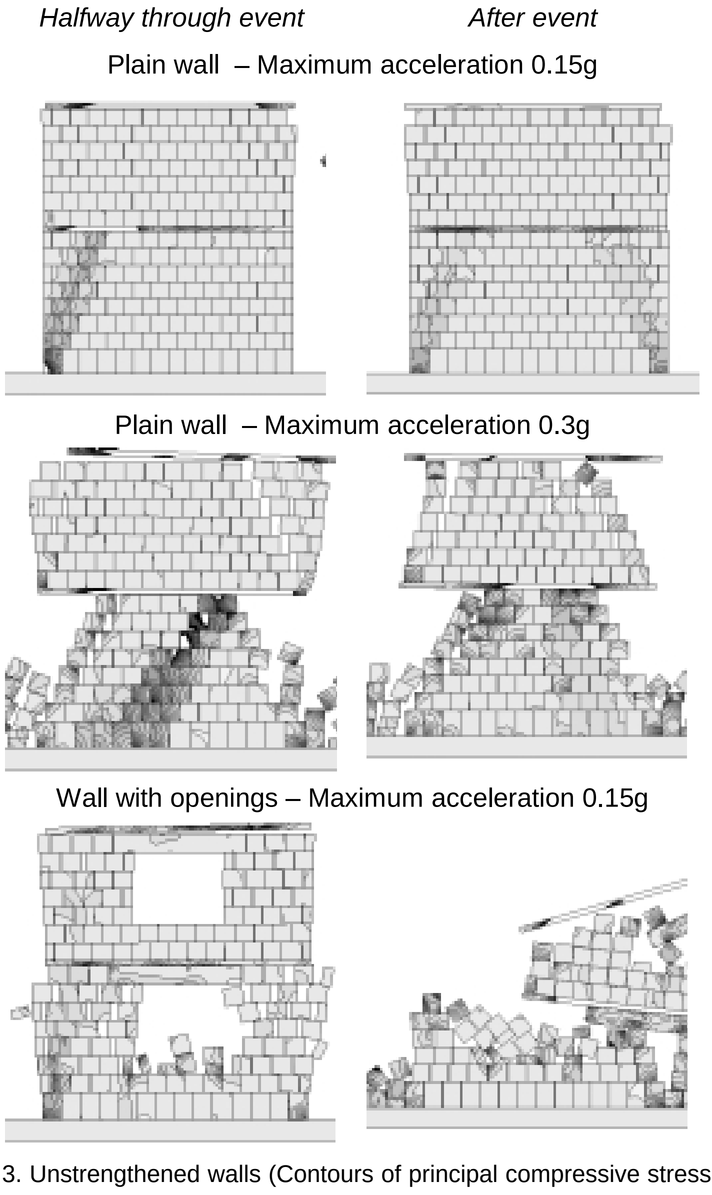


Figure 3. Unstrengthened walls (Contours of principal compressive stresses)

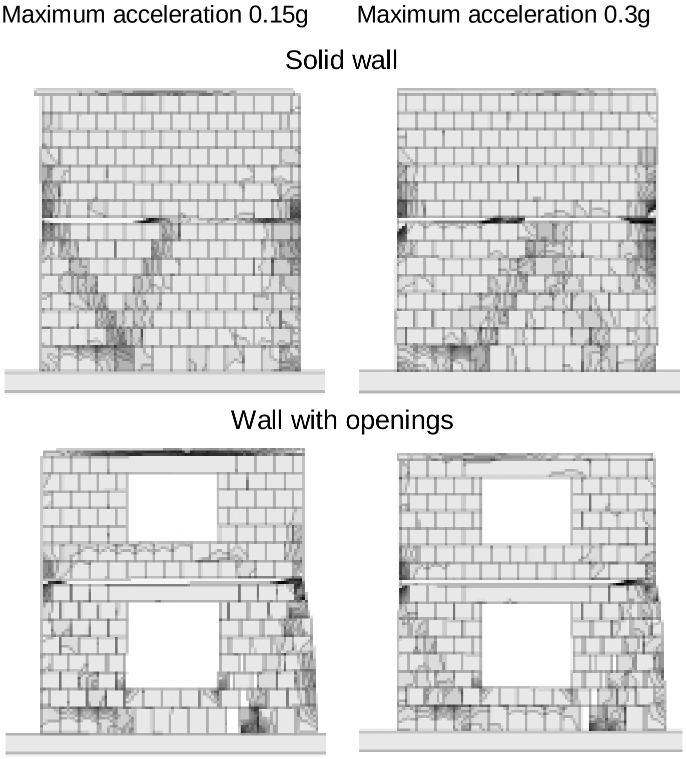


Figure 4. Combined reinforcement arrangements
(Contours of principal compressive stresses)

in Figure 4. Identical schemes were applied to both the plain wall and the wall with openings. Strengthening arrangements are more comprehensively described elsewhere (Brookes, Swift, 2000).

The plain wall remains intact throughout the seismic event with the reinforcement controlling the development of cracking. Even under 0.3g loading, although higher locked in stresses are predicted little damage is evident. Without reinforcement, blocks left unarrested rapidly propagate failure mechanisms leading to collapse.

The wall with openings is similarly improved except that considerable cracking occurs to the first storey with appreciable dilation on one side. Although the improvement compared with the unstrengthened wall is dramatic debonding of some reinforcement has marked the beginning of a failure mechanism and continued shocks would be very damaging.

CONCLUDING REMARKS

By combining the discrete element technique with a finite element formulation for reinforcement, numerical models are beginning to be used that allow rapid evaluation of the relative performance of reinforcement based retrofitted strengthening. This process has been illustrated using a plane shear wall subjected to simplified hypothetical ground movements. This practice is now well established for strengthening masonry arches to carry static loads.

The generic approach to masonry representation coupled with ever expanding computational resources enables much more complex structural arrangements to be investigated. An illustrative analysis of the façade of an ancient masonry building subjected to strong ground movement is shown in the introductory figure.

Current developments include the application of more advanced interface models to represent mortar by the addition of combined Mode I fracturing, Mode II fracturing, and compressive failure to the simple friction models used here. This more advanced representation is essential if masonry with significant tensile strength is to be investigated but is perhaps of less interest for historic buildings.

Advances are also being made in the application of 3D DE models which to date have not been industrially robust.

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Job Opportunity at GeoHazards International

GeoHazards International (GHI) (www.geohaz.org), a non-profit global alliance for natural disaster preparedness, is seeking a full-time Project Manager for its Palo Alto, California office. The post will involve working with GHI staff and its international partners to plan and implement projects in the field of earthquake risk reduction and preparedness in developing countries. The job description will include travel to developing countries and working with local governments and NGOs.

The applicant will require at least 3 years of experience in project management and hold a bachelor's degree in civil engineering or an Earth science; strong writing skills are also required. Applicants should have legal authorisation to work in the USA without sponsorship. Applicants should contact GeoHazards International, GeoHazards International, 200 Town and Country Village, Palo Alto, CA 94301, USA, Phone: 00-1-650-614-9050, Fax: (650) 614-9051, e-mail: info@geohaz.org.

Imperial College to Re-launch MSc in Earthquake Engineering

The Department of Civil and Environmental Engineering at Imperial College has announced that the Master of Science course in Earthquake Engineering will run again from October 2003. The MSc course, which was originally launched in 1987, was suspended in October 2001 due to the departure of Professor Amr Elnashai to the USA at the same time as the course was to be launched in a new format as a degree in Earthquake Engineering and Risk Management under an EPSRC Masters Training Package.

The MSc course will run again from next year in a modified format as part of a comprehensive reorganisation of postgraduate courses in civil and environmental engineering at Imperial College that comes into effect for the 2003-4 academic session. The new format for delivery of the MSc courses will be based on a coordinated structure and timetable that will allow for many different options under the broad headings of Advanced Structural Engineering, Geotechnics, Hydrology and Environmental Engineering, and Transport, any of which can also be combined with Business Management or Sustainable Development.

The MSc course in Soil Mechanics and Engineering Seismology, which has been run for more than 30 years, will continue to be available as an option amongst Geotechnics courses, and Earthquake Engineering will be offered as one of the courses in Advanced Structural Engineering. Enquiries regarding the Earthquake Engineering MSc should be directed to Dr Ahmed Elghazouli, tel: 020-7594-6021, e-mail: a.elghazouli@ic.ac.uk.

Julian Bommer

Marie Curie Fellowships at the ROSE School, Pavia, Italy

The European School of Advanced Studies in Reduction of Seismic Risk (ROSE) was founded in the autumn of 2000, with the aim of providing higher-level education in the field of earthquake engineering. The syllabus offers a comprehensive set of subjects covering applied mechanics, structural engineering, earthquake engineering, engineering seismology and soil dynamics, with emphasis on both theoretical background and design considerations. The organisation of the ROSE School is based on a relatively short permanence of scholars with extremely high qualification. Indeed, all lecturers at the School are internationally recognised experts in the field, coming from a number of distinguished institutions from around the world.

In December 2001, the European Commission has attributed to the ROSE School the status of Marie Curie Training Site, acknowledging the high quality of its earthquake engineering training programme. The signed agreement provides funds that allow the financing of postgraduate scholarships with a duration of 3 to 12 months. The bursaries, with a value of 1200Euro/month, may be awarded to PhD students currently undertaking research work on earthquake engineering related topics, who might wish to spend a relatively short period of time at the ROSE School, attending taught courses or carrying out research work under the supervision of one of the Faculty members.

Further information and detailed instructions on how to submit an application can be found at the ROSE School website, indicated below.

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Rui Pinho

NOTABLE EARTHQUAKES DECEMBER 2001 - FEBRUARY 2002

Reported by British Geological Survey

YEAR	DAY	MON	TIME UTC	LAT	LON	DEP KM	ML	MB	MS	LOCATION
2001	**01**	**DEC**	**21:14**	**56.70N**	**5.15W**	**7**	**1.5**			**BALLACHULISH**
			Felt throughout the Ballachullish area with maximum intensities of 4 EMS.							
2001	**02**	**DEC**	**13:01**	**39.40N**	**141.10E**	**124**		**6.1**		**E HONSHU, JAPAN**
			Felt from southern Honshu to central and eastern Hokkaido.							
2001	**04**	**DEC**	**05:57**	**15.35S**	**72.52W**	**33**		**5.5**	**5.6**	**SOUTHERN PERU**
			Two people were killed at Puncunco, at least five people were injured at Chuquibamba and approximately 30 houses were damaged in the Condesuyos Province.							
2001	**16**	**DEC**	**13:25**	**53.68N**	**2.00W**	**10**	**2.6**			**HALIFAX,W YORKS**
			Felt throughout Halifax and Todmorden with intensities of 4 EMS.							
2001	**18**	**DEC**	**04:02**	**23.95N**	**122.73E**	**14**		**6.3**	**7.3**	**TAIWAN REGION**
			Felt strongly throughout much of northern Taiwan.							
2001	**19**	**DEC**	**20:58**	**56.24N**	**3.74W**	**5**	**2.1**			**BLACKFORD**
			Felt throughout Glendevon with maximum intensities of 4 EMS.							
2001	**22**	**DEC**	**22:52**	**9.61S**	**159.53E**	**16**		**6.2**	**7.0**	**SOLOMON ISLANDS**
			Felt throughout the Solomon Islands.							
2002	**02**	**JAN**	**17:22**	**17.60S**	**167.86E**	**21**		**6.3**	**7.5**	**VANUATU ISLANDS**
			Several people were injured, two bridges were destroyed and buildings and roads were damaged on Efate.							
2002	**03**	**JAN**	**07:05**	**36.10N**	**70.70E**	**129**		**5.8**		**HINDU KUSH REGION**
			At least one person was injured.							
2002	**10**	**JAN**	**11:14**	**3.21S**	**142.43E**	**11**		**6.0**	**6.6**	**NEW GUINEA**
			One person was killed and approximately 200 houses were destroyed in the Aitape area.							
2002	**14**	**JAN**	**15:36**	**19.38S**	**69.23W**	**33**		**5.5**	**5.2**	**NORTHERN CHILE**
			Minor damage occurred to houses in the epicentral area.							
2002	**17**	**JAN**	**20:01**	**1.68S**	**29.10E**	**15**		**4.7**		**LAKE TANGANYIKA**
			Several people were killed and at least 300 buildings were destroyed in the Gisenyi area of Rwanda. This is one of the largest of a series of earthquakes associated with the eruption of Volcan Nyiragongo.							
2002	**03**	**FEB**	**07:11**	**38.56N**	**31.11E**	**10**			**6.5**	**AFON, TURKEY**
			At least 45 people were killed and approximately 300 people were injured and hundreds of homes were destroyed.							
2002	**12**	**FEB**	**19:13**	**51.70N**	**3.25W**	**8**	**3.0**			**BARGOED**
			Felt with intensities of 4 EMS throughout the epicentral area.							

Issued by: Bennett Simpson, British Geological Survey, March 2002.

Online Report

The following article is available as a downloadable pdf file from High-Point Rendel's website:

'Effect of the 1999 Earthquakes on Seismically Isolated Viaducts on the Istanbul to Ankara Motorway, Turkey.'

Follow the links from:
http://www.hprendel.com/techarts.html

Forthcoming Events

12 July 2002
Innovative Approaches to Earthquake Engineering
(Joint Seminar with Wessex Institute of Technology)
ICE 9.30am to 4pm

31 July 2002
Review of Field-Based Procedures for Evaluating Liquefaction Potential during Earthquakes - Professor I.M.Idriss
(Joint Seminar with BGA)
ICE 5.30pm

9-13 September 2002
12th European Conference on Earthquake Engineering

25 September 2002
Earth Observation for Disasters

30 October 2002
Seismic Design Guidelines for Port Structures

SECED Newsletter

The SECED Newsletter is published quarterly. Contributions are welcome and manuscripts should be sent on a PC compatible disk or directly by Email. Copy typed on one side of the paper only is also acceptable.

Diagrams should be sharply defined and prepared in a form suitable for direct reproduction. Photographs should be high quality (black and white prints are preferred). Diagrams and photographs are only returned to the authors on request. Diagrams and pictures may also be sent by Email (GIF format is preferred).

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SECED

SECED, The Society for Earthquake and Civil Engineering Dynamics, is the UK national section of the International and European Associations for Earthquake Engineering and is an affiliated society of the Institution of Civil Engineers.

It is also sponsored by the Institution of Mechanical Engineers, the Institution of Structural Engineers, and the Geophysical Society. The Society is also closely associated with the UK Earthquake Engineering Field Investigation Team. The objective of the Society is to promote co-operation in the advancement of knowledge in the fields of earthquake engineering and civil engineering dynamics including blast, impact and other vibration problems.

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