THE VULNERABILITY TO EARTHQUAKES OF LOW-STRENGTH MASONRY STRUCTURES

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ABSTRACT The paper reviews the work of a newly-formed multidisciplinary group to consider ways of reducing the vulnerability of buildings of traditional construction in seismic areas. The problems of assessing vulnerability are discussed, and the preliminary results of recent field studies in Northern Pakistan and Southern Italy are summarised.

In the great siesmic belt which stretches from the Mediterranean across Turkey and Iran to the Himalayan mountains, the vast majority of people live today in buildings of moderate or high vulnerability to earthquakes. Traditional building types have developed from three primary constraints:

(1) Arid or semi arid climates, in which the difference between day and night temperatures is considerable, so that massive roofs and walls are needed to create comfortable indoor conditions.

(2) A severe shortage, and often complete absence of timber, or indeed any other building material capable of carrying tension.

(3) Economic deprivation and sometimes extreme poverty, which dictate that only local materials and 'self-build' methods can be used.

Throughout this area, dwellings consisting of massive but weakly bonded masonry walls of adobe or random rubble stonework, and supporting heavy mud or tiled roofs, are the rule. And since the structures of such dwellings are inherently unable to resist more than a very limited amount of shaking force (and indeed in many cases would by the standards of industrialised countries be considered statically unsound even under their normal gravitational loading), the occurrence of an earthquake is liable to cause a major disaster in which many thousands of buildings are destroyed and large numbers of people are killed by or trapped under falling masonry. Even without considering the irreplaceable nature of these losses, cost of the relief operations and of the economic disruption caused by such events make it necessary for all administrative and financing agencies involved to consider whether there are not ways in which these vulnerable communities could not be provided with protection against earthquakes, in a manner analogous to those used for other natural hazards, such as flood or erosion protection measures.

Although this is an old problem, it is one which surprisingly little progress has been made in recent years, particularly when compared with the considerable advances which have been made in the engineering theory of earthquake-resistant design. One of the reasons for this lack of progress has been the large gap between what engineers have deemed the minimum adequate standards of earthquake protection, and what the recipients of that protection have been able to afford, or at least willing to pay for it. Meanwhile the increasing economic marginalisation of rural populations everywhere in the region and the diminishing availability of traditional building materials appears to be creating conditions of increasing vulnerability for these populations.

It was against this background that a multi-disciplinary working group was recently formed in the U.K. to look for new approaches to this problem. Recognising that technical measures would be no more likely than before to provide adequate solutions without an understanding of the wider social and economic context, the membership of the group included specialists in social sciences (anthropologists and geographers) as well as engineers and architects, and maintains strong links with seismologists and geologists.

One of the underlying convictions of the group is that ancient societies have been more aware of the earthquake risk than is generally recognised, and that many of the traditional building techniques used in seismic zonesin different parts of the world (notably those of China, Japan and South East Asia) have proved themselves over time to be very well adapted to earthquakes. The group therefore believe that one hitherto little explored way of making more progress in design of low-cost buildings to resist earthquakes is to study and learn from these techniques, to find ways in which they could be modified to improve their performance or adapted for use elsewhere in the world. This problem is discussed in more detail elsewhere (1).

A second conviction of the group is that there is still a severe dearth of experimental work on the performance of small buildings, particularly data which is based on field observation. Progress in understanding the behaviour of small buildings in earthquakes and hence earthquake resisting design can only be made if the response of buildings to known ground movements can be observed. This can be done in a broad way by the observation of the performance of buildings in earthquakes, but the most useful observations will be made where the local ground movements have been measured by strong motion instruments, of which there are still very few in the areas being discussed. A second approach is the modelling of structures for testing in the laboratory. Although further considerable modelling difficulties present themselves (which have been discussed elsewhere (2)), the group intends to work towards linking field study with laboratory study of existing structural form. Laboratory models could then be used to study the effectiveness of various possible design modifications on earthquake resistance; successfully tested modifications could then become the basis for design guides for local builders in modifying and strengthening buildings in seismic areas.

A third conviction is that neither laboratory nor field studies should be undertaken in isolation from the question of developing appropriate programmes for the implementation of the results of these studies; the economic and administrative problems of implementation of modification programmes have in the past invalidated research work to such an extent that it is now believed vital at all stages to consider these problems in devising technical investigation programmes.

The initial stimulus for the formation of the group was an invitation from the Royal Geographical Society to take part in its 1980 Karakoram Project, a large scientific expedition to the Karakoram region of North Pakistan, recently made accessible by the Karakoram highway. This region presented an ideal opportunity for a field study since it experiences a relatively high frequency of damaging earthquakes (most recently in 1974), and has an interesting variety of vernacular building types using combinations of stone and timber, some of which have been reported as being resistant to earthquakes. The working group spent 2 months studying vernacular building types and the earthquake risk (as well as other hazards) between June and September 1980.

A second field study was carried out in March 1981 by the same group in Campania, Southern Italy, on the effects of the November 1980 earthquake in that region. Again the effects of the earthquake on vernacular building types was one of the main interests. The engineering aspects of both of these studies were financed by the Science Research Council, and both will be described in greater detail in papers to be published in due course. Tis present paper presents a brief interim review of the main objectives and activities and some preliminary conclusions of each of these studies.

Field study in Pakistan

The principal objective of this study was to examine traditional or vernacular building types, and to investigate what relationship there was between the existing forms of buildings and settlements and the vulnerability of these settlements to earthquakes and natural hazards; at the same time it was intended to look at local awareness of these hazards, and the extent to which the people themselves would be willing to modify their traditional houseforms to make them less vulnerable.

Two settlements in the region were chosen for detailed study. One of these settlements, Pattan in Kohistan on the Indus, had been very seriously damaged in the earthquake of Dec 28, 1974, and the report of the UNESCO mission (3) had stated that some of the buildings had been built using traditional techniques which made them less vulnerable. A second settlement chosen, Barculti in the Yasin valley, had not itself experienced a recent earthquake, but was in an area of known seismic activity; buildings in this area were built according to the Chitrali tradition, which anthropological writers (4) had suggested included earthquake-resisting features. Two more settlements were visited for shorter periods, Ghorharabad on the slopes of the Indus valley at an altitude of 3,000m, more inaccessible and using building techniques different from either of the other two settlements; and Garnish in the Hunza Valley. In neither of these two places is there a recent history of seismic activity. Fig. 1 shows the location of each of these settlements.

In each of these settlements detailed observations and measurements were made of the settlement forms and their location in relation to possible rock falls and flooding, and of the form of construction of typical individual buildings.

The house types will be described in detail elsewhere (5). One example, the typical form of dwelling in Barculti is shown in figs. 2 and 3. The standard living room is almost square, approximately 6m across, surrounded by low windowless walls of thick random rubble masonry: the main living space is defined by four large square timber columns, which support the primary beams which in turn carry the roof. An important feature of these columns is that their bases rest on horizontal timber base-plates, and the primary beams rest on them without any form of connection other than that provided by friction. Resting on the primary beams are a series of smaller transverse beams spanning laterally to the side walls, and also, over the centre space, a pyramidal structure of diagonally placed beams which define the only opening to the space, a smoke-hole. The roof structure is covered with a layer of mud between 300 and 500mm thick.

Very similar structures are found in the Chitral Valley, further west, geographically and ethnically related to the Yasin Valley, and have been described by Hassam ul Mulk and Staley (4) who write "the Chitralis claim that this combination of wood and stone is particularly resistant to earthquake shocks," and that "when there is an earthquake the women run to the Sher-o-tun (Shiri-Dung fig. 2) and cling to it as the safest place in the house."

However, it was one of the most strongly formed conclusions of this study that, in the Yasin Valley certainly, there is very little awareness of the risk of earthquakes. In relation to the other hazards faced by the people of these valleys, (of flooding, rock falls or mudslides and of soil erosion) which derive from the unstable and rapidly changing landforms - the earthquake risk is perceived as being very remote, in spite of the occurrance during the last 50 years of two earthquakes large enough to cause damage in nearby valleys. In consequence there is little awareness of the need for or demand for earthquake-resistance in local house forms. Such earthquake-resistance as these house-types do possess is presumably then rather accidental than conscious, being in all probability the result of the introduction at some earlier time of house forms derived from the cultural and physical requirements of the Chitral valley. A further study of the earthquake-awareness of that region would have been valuable, but unfortunately the current Afghanistan-Pakistan border situation made it impossible.

In the absence of any data on the performance of this Yasin building type in past earthquakes, the extent to which these structures would in practice prove to be earthquake-resistant could not be deduced from the field study; and one of the objectives of the study was to obtain a sufficiently detailed structural description to enable them to be modelled for subsequent theoretical analysis, or experimental analysis using small-scale models. In addition to the detailed surveys, descriptions and samples of building materials, it was also decided to attempt direct measurement of the dynamic response characteristics of selected buildings. This was done by means of a controlled frequency vibrator, attached to the roof structure, the response of which was measured at various points by suitably placed accelerometers.
By this means it was possible to determine directly the natural modes of vibration, natural frequencies and damping characteristics of these buildings, and also to observe the degree of connection between the structural elements (roof structure, walls, columns, etc). The method is not new; it has recently been used by the U.K. Building Research Establishment for studies of the wind response of tall buildings (6). But it may be the first time that it has been applied to buildings of this type. The method is of course subject to the severe limitation that only very small vibration response can be studied, which, although it may give useful information about the conditions prior to material breakdown in earthquakes, gives little clue to the response of the

structure in major shaking once irreversible structural changes have occurred. It is also subject to the severe practical limitation that householders are inclined to be reluctant to offer their houses for such testing, which at best is an inconvenience, but also requires confidence in the ability of the engineers to ensure that it proves as non-destructive as they claim it to be. In the event it was possible to find enough time and develop enough confidence to test only two houses and a number of walls, all in Barculti Village.

The results of these tests are interesting and will be described in detail in a forthcoming paper (7). Very clear resonance peaks for the buildings, were identifiable at frequencies in the range 0.10 to 0.15 secs for vibration in the longitudinal plane of the primary roof structure; and it was also observable that even at small amplitudes there is a clear separation between the motion of the column-supported roof and the longitudinal walls. These observations suggested the possibility of the modelling of the structure as a simple column-beam system, in which the columns are not connected either at their head or base, but are free to 'rock' under lateral earthquake loading; and a study of this system is in progress.

Field study in Italy

The general objective of this study was to examine damage in a number of the settlements affected by the earthquake of November 23 1980. The survey was planned to take place during March 1981 at a time when immediate relief needs were largely met, but before substantial demolition and rebuilding had been carried out.

As in Pakistan, it was proposed to study vernacular building techniques, (both traditional and more modern) but also, in this case, to assess the performance in the earthquake of different building types in areas affected by ground motions of different levels.

More than this, it was also intended to obtain some assessment of the relative significance of age and condition of the structure, of orientation, of subsoil conditions and of topography on the degree of damage caused to buildings; and to look also at the damage to other structures, towers, roads, embankments etc.

Some basis for this work was provided by the intensity mapping already carried out by CNR (8), see fig. 4, and potentially even more significant, by the records of 20 strong motion instruments of the ENEL network which were triggered by the earthquake (9). It was intended to use the positions of these strong motion instruments as the centres for localised damage surveys, so that building performance could be directly compared to ground movements. It was considered important to restrict these surveys to the very immediate locality of the strong motion instruments, in order to limit any effects from the variation of ground and topographical conditions.

However, investigation showed that none of the instruments was located in the epicentral region (MSK intensity X, fig. 4) and only one was in the region of MSK intensity IX. Moreover, the instruments were placed in electrical substations, and they were in most cases removed from the old town centres to places on the outskirts of the towns, where there were fewer, more recently constructed buildings, and where damage was rather light.

The damage surveys actually carried out therefore consisted of

(a) Localised surveys of all buildings within approximately 250m of the strong motion instruments, at six stations located near the epicentral region (Auletta, Brienza Bagnoli, Irpino, Bisaccia, Calitri and Sturno)

(b) More extensive damage surveys in two towns; Salvitelle, approx. 40km from the epicentre, and assigned MSK VIII by the CNR survey, and Lioni, very close to the epicentre and assigned MSK X by the CNR. In both of these surveys a substantial representative sample of the buildings in the town was surveyed, there being insufficent time for a complete survey.

The damage classification system used was a 7-point scale using crackwidths as an indicator, based on that devised by the Building Research Establishment for classification of damage due to foundation settlement in the U.K. The Scheme is shown in Table 1. For each building surveyed the information recorded also included data on its situation and orientation, form and materials of construction, age and condition, and assessments of its serviceability and ability to withstand aftershocks; and in the case of masonry buildings a sketch of the pattern of cracking.

Table 1. Damage classification scheme.

Damage level	Interpretation
0	No damage
1	Light, superficial non structural damage
2	Small cracks $<$ 5mm. width
3	Cracking 5mm. $<$ max. width $<$ 10mm.
4	Cracking $>$ 10mm.
5	Partial collapse
6	Total collapse

Altogether 416 buildings were surveyed in the 8 surveys. More than three quarters of all buildings surveyed fell into one or other of two categories. By far the largest number (58.5% of all buildings surveyed) were 2 or 3 storey buildings of random rubble masonry construction, with either timber or steel joist floors, and with tiled roofs supported on timberjoists.

In 1858, following the great Neopolitan earthquake of the previous year, Robert Mallet was sent by the Royal Society to investigate. His account (10) begins with a description of the building methods of the region part of which is quoted below:

> "The general style of construction of walls, even in first class buildings, consists of a coarse, short-bedded, ill-laid rubble masonry with great thickness of mortar joints, very thick walls, without any attention to thorough bonding whatever... The floors are formed of joists of fir timber.. from 6 to 9 inches in diameter, placed about 3 feet apart. The ends are inserted some inches into the walls but are neither bedded on nor connected by any bond timbers, none of which are ever placed in the walls... The roofing also usually consists of round fir timber. The framing is of the simplest character. It consists commonly of principal rafters at 3 to 5 feet apart connected by a rude collar brace, of round fir also, trenailed or bolted to the rafters. The feet of the rafters sometimes rest on a wall plate of squared or half round timber, but often bed directly on top of the wall".

The form of construction which was described by Mallet is still very largely prevalent in the region today although with some modifications:

(1) many of these buildings have, without strengthening of the supporting structure, had additional third or even fourth stories added in newer materials.

(2) the timberfloors described have, in many cases been removed and replaced by concrete floors supported by steel joists and ceramic planks; but, as before connected neither to the wall nor bonded laterally to make the floors monolithic.

There is little doubt that these modifications have generally weakened an already weak structural system; accordingly this type of building is every bit as vulnerable as those which were condemned by Mallet in 1858.

The second major type of building is that of more recent construction. This type (17.2% of buildings surveyed) is of 2 to 4 stories and has a reinforced concrete frame. The frame consists of columns of 300 to 400mm diameter supporting an insitu floor slab of ceramic plank filler construction, and usually a pitched reinforced concrete slab roof. The walls are infilled after the construction of the frame and commonly consist of two skins of ceramic blocks not bonded to each other or to the frame. In this type of construction there are no shear walls, and lateral strength is provided only by flexural strength of the connection of column to the floor structure. It is not designed for any seismic forces.

The remaining 24% of buildings were a mixture of masonry buildings mostly of more recent construction, and some including r.c. floor or roof slabs.

Histograms of damage for the random rubble masonry buildings in Lioni and Salvitelle are shown in fig. 5. A striking feature of these histograms is the very considerable spread of damage, even within one building type. This means that many factors other than location and building type need to be considered in explaining damage levels. It may be as Mallet claimed in his 1857 report, that the orientation of a masonry building to the main direction of the shock affects its performance. It is certain also that not only subsoil conditions but also topography have a strong affect on the degree of shaking experienced. There were remarkable examples in several towns of a complete change in the pattern of damage as subsoil conditions changed from hard rock to soft rock or alluvium. In Salvitelle, however, a similar variation in damage could not be clearly attributed to a change in subsoil conditions or building types; but considerable variation (by a factor of 5) was observed in the peak readings of 5 seismometer recordings of the same minor after shock all within an area of 250 m of each other: this suggested the possibility of a strong topographical effect on damage distribution, which merits further investigation.

For rubble masonry buildings the level of damage in terms of percentage of damaged buildings (damage 2 or above) for all the surveys is shown against the intensity level assigned to that town in the CNR survey (8) in fig 6: the correlation between assigned intensity and damage is surprisingly poor, and damage levels are on the whole lower than would be expected for this class of masonry at the MSK intensity levels assigned (11).

Further analyses of the data for the Italian survey, including comparisons with the strong motion instrument records, are in process of being carried out, and will be reported in due course.

<u>Conclusions</u>:

Tentative conclusions for the Pakistan and Italian field studies are :

1. In both Italy and Pakistan, buildings of random stone masonry without independent structural frames are highly vulnerable to earthquakes.

2. In both areas, low income and lack of awareness of the earthquake risk are severe obstacles to any major or rapid

reduction in vulnerability; even buildings built of more modern materials have been shown to be very vulnerable, because of poor construction techniques and a lack of understanding of the basic principles of anti-seismic construction.

3. In Pakistan, there is some evidence that an independent timber roof support system reduces vulnerability, but the effectiveness of this not yet clear.

4. It is possible to obtain information on the dynamic characteristics of buildings of traditional construction under small vibrations using a simple portable vibrator and accelerator, but such tests can be difficult to organise in the field.

5. The usefulness of damage surveys to obtain information on vulnerability of traditional construction is limited by inadequate knowledge of ground movement. Intensity level is a very crude measure, and is subject to considerable error. Strong motion instrument records are potentially more valuable, but even in Italy, which has one of the most extensive networks, the density and positioning of stations is inadequate as a basis for damage surveys.

6. The methodology of damage surveys needs to be further refined so that they can be used for :

   (a) Studies of a wide variety of traditional building types

   (b) Studies of the effect of modifications in traditional technologies

   (c) assessment in quantitative terms of damage distribution, so that vulnerability of similar building types can be predicted

   (d) identification of the major factors (e.g. orientation, ground, topography etc.) affecting building damage

   (e) constructing theoretical and laboratory models of typical buildings

   (f) comparison with strong motion instrument records to identify the characteristics of earthquakes which best correlate with damage.

7. There is great value in undertaking field studies with a multi-disciplinary team comprising engineers, architects, anthropologists, geographers, geologists and seismologists; lack of any one of these perspectives on the earthquake phenomena would have greatly reduced the value of the studies undertaken. But there is also much to learn about the successful management of such an interdisciplinary group in the field.

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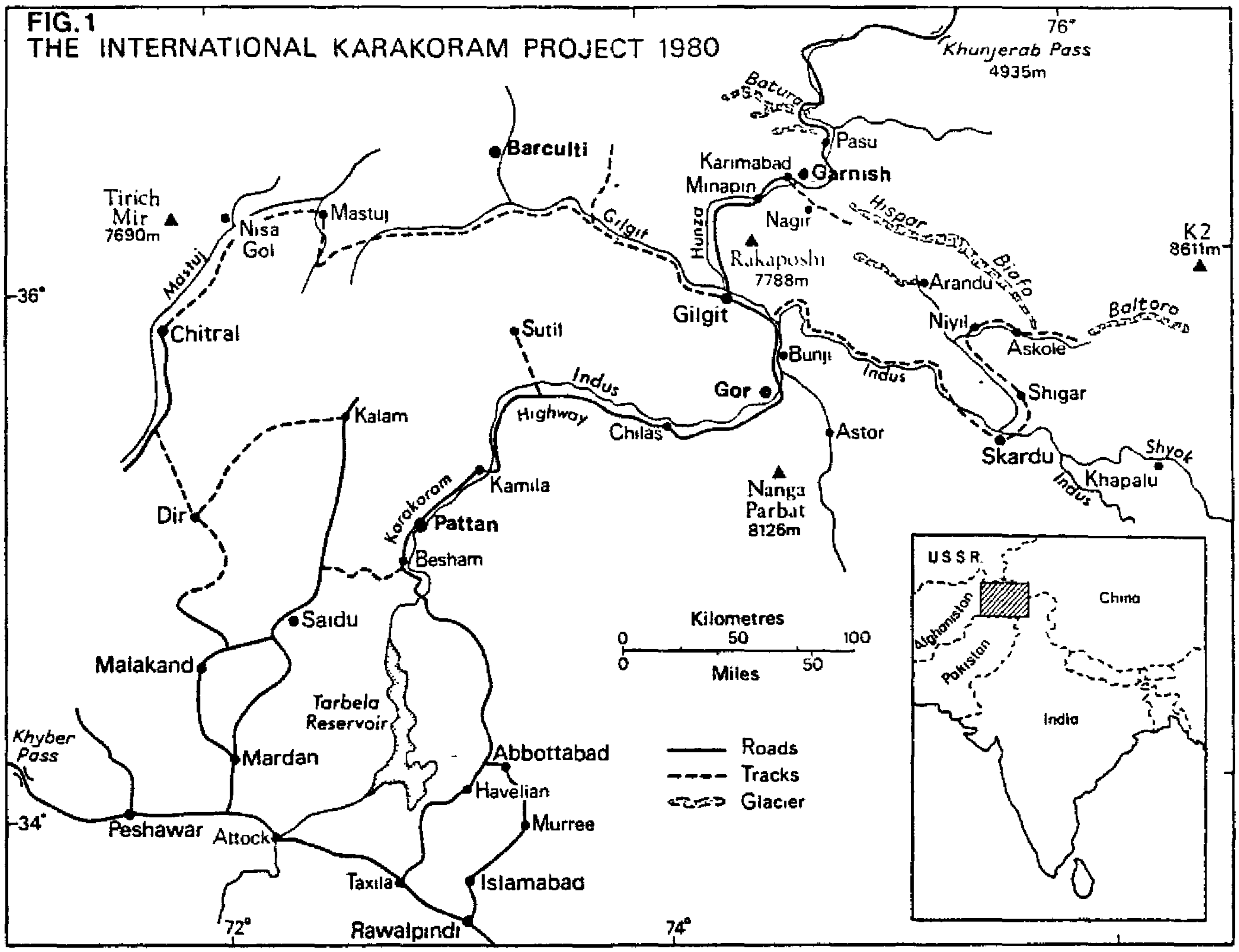


FIG. 1
THE INTERNATIONAL KARAKORAM PROJECT 1980
Khunjerab Pass
4935m
Batura
Pasu
Karimabad
Garnish
Minapin
Hunza
Nagir
Hispar
Rakaposhi
7788m
Biafo
Arandu
K2
8611m
Baltoro
Niyil
Askole
Gilgit
Bunji
Indus
Shigar
Skardu
Shyok
Khapalu
Astor
Nanga
Parbat
8126m
Gor
Chilas
Indus
Highway
Sutil
Barculti
Gilgit
Tirich
Mir
7690m
Nisa
Gol
Mastuj
Mastuj
Chitral
Kalam
Dir
Kamila
Karakoram
Pattan
Besham
Saidu
Malakand
Mardan
Tarbela
Reservoir
Abbottabad
Havelian
Murree
Islamabad
Taxila
Rawalpindi
Attock
Peshawar
Khyber
Pass
Kilometres
0
50
100
0
Miles
50
Roads
Tracks
Glacier
U.S.S.R.
China
Afghanistan
Pakistan
India
76°
36°
34°
72°
74°

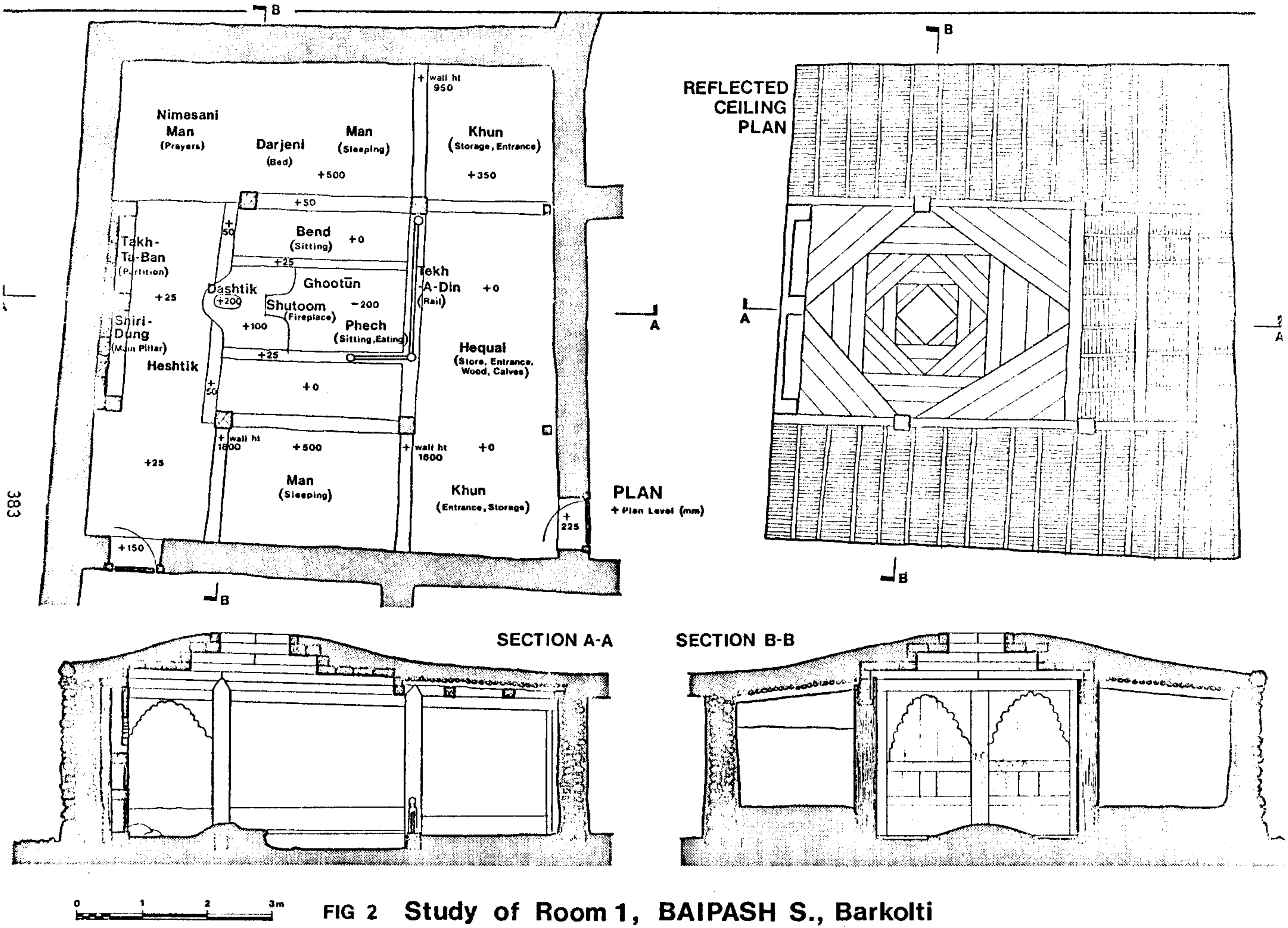
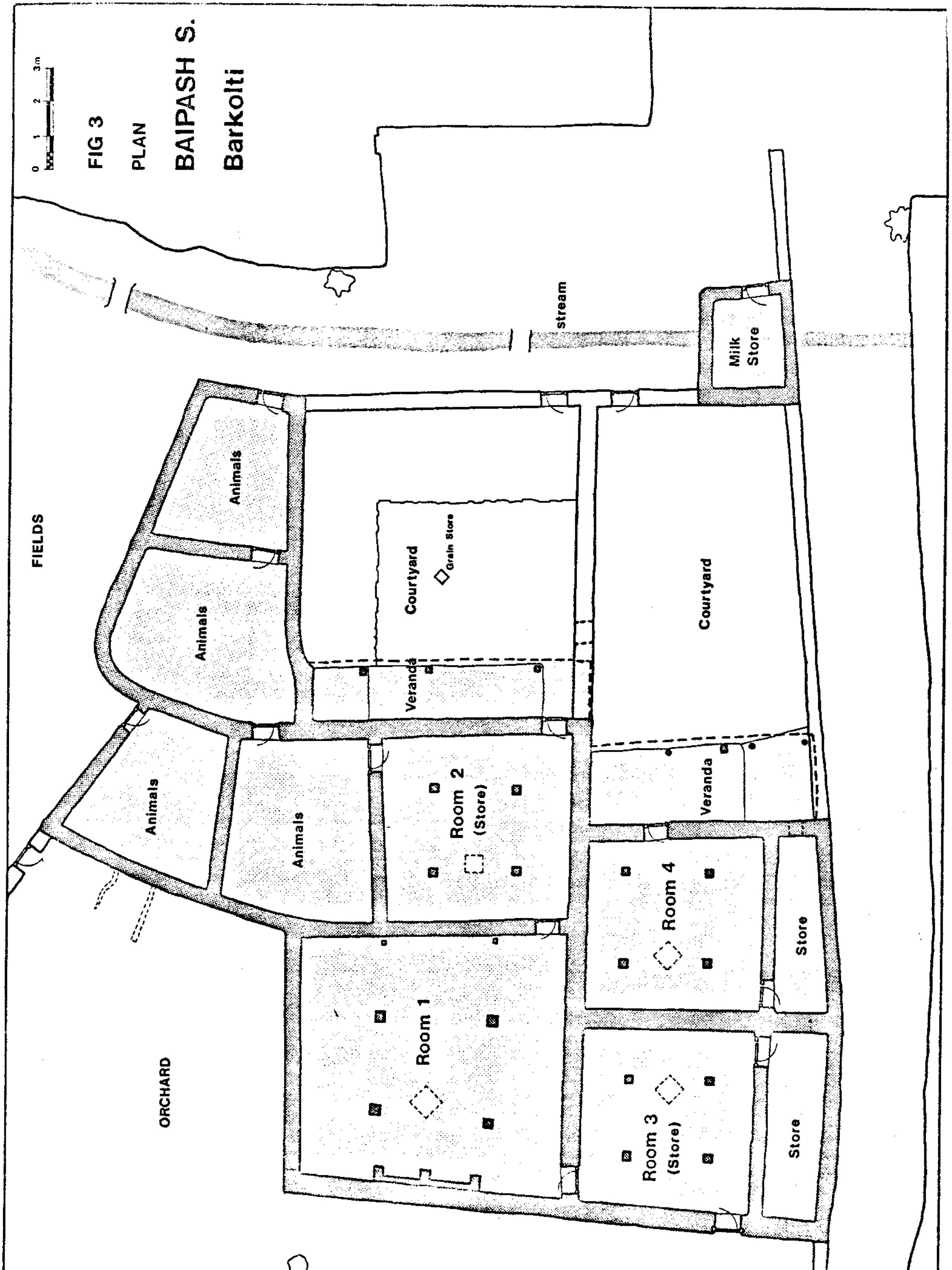


FIG 2 **Study of Room 1, BAIPASH S., Barkolti**


0 1 2 3m
FIG 3
PLAN
BAIPASH S.
Barkolti
FIELDS
ORCHARD
stream
Milk Store
Animals
Animals
Animals
Animals
Courtyard
Grain Store
Courtyard
Veranda
Veranda
Room 2 (Store)
Room 1
Room 4
Room 3 (Store)
Store
Store

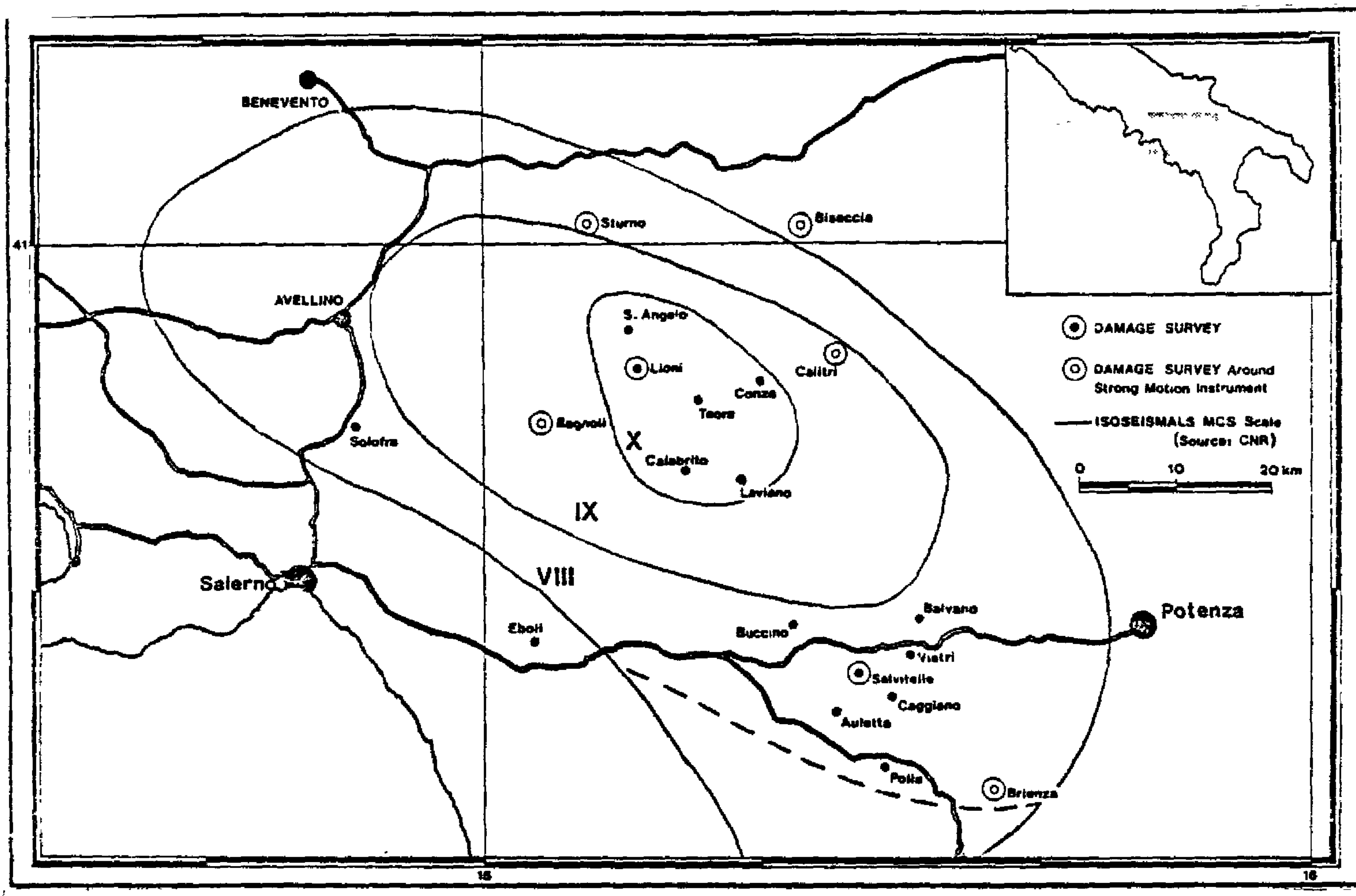
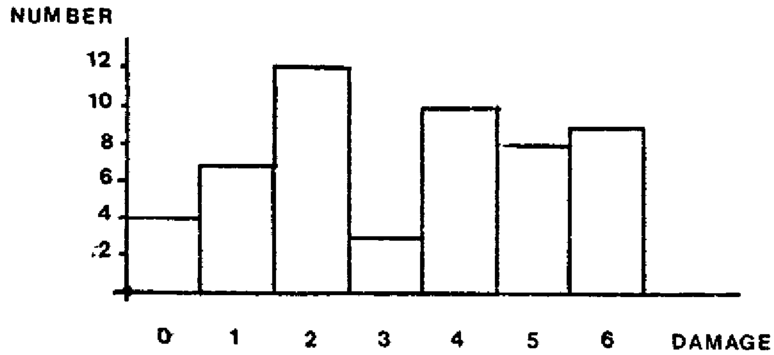
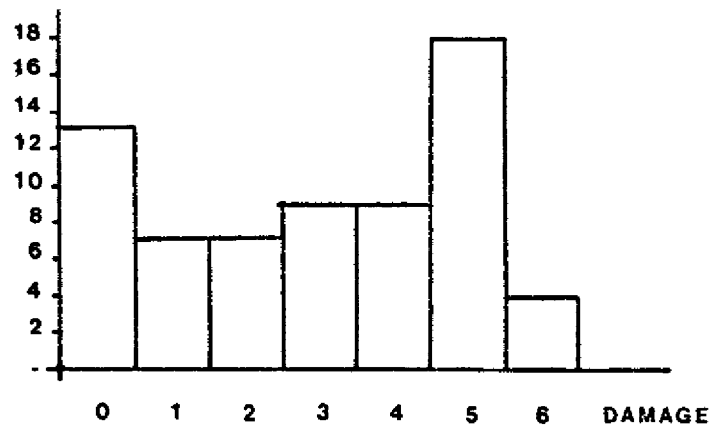


FIG 4 ITALIAN EARTHQUAKE 23.11.80



LIONI



SALVITELLE

FIG.5 DAMAGE DISTRIBUTION
Masonry buildings in Lioni and Salvitelle

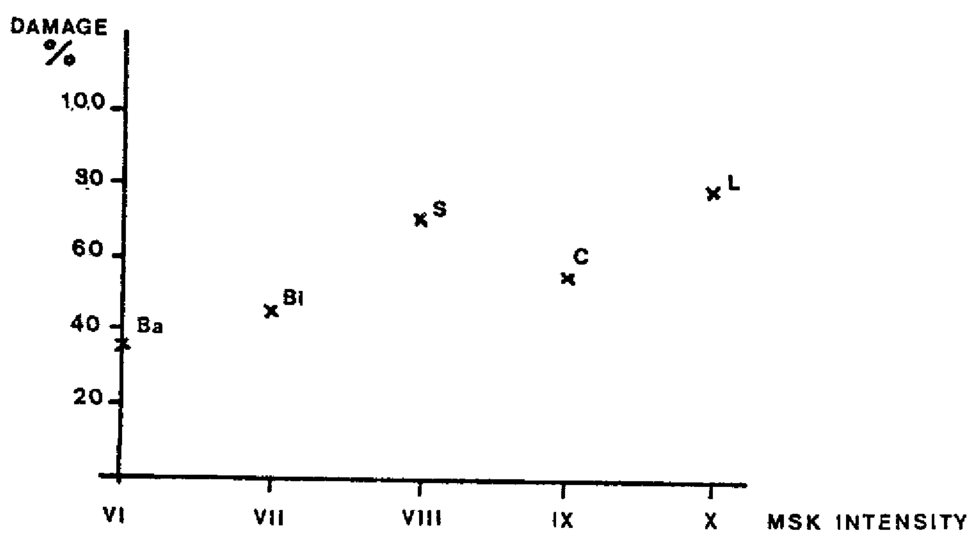


FIG. 6 MASONRY BUILDINGS
Damage at each assigned intensity
(percentage of buildings with damage level ⩾2)