THE ASSESSMENT OF EARTHQUAKE FELT INTENSITIES

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SUMMARY

The definition of felt intensity has been greatly influenced by the problem of making assessments under extremely varied field conditions. Difficulties in constructing and applying a satisfactory intensity scale, and the limitations of some scales in common use are discussed. Intensities cannot be closely correlated with ground accelerations, but they can be assessed with a high degree of mutual consistency. Instrumental measurements of acceleration are scarce, and likely to remain so. When treated statistically or presented in the form of isoseismal maps, estimates of intensity can be used for the investigation of differences in foundation conditions, characteristic and anomalous propagation of earthquake motion, and similar problems of seismological and engineering importance.

INTRODUCTION

The observatory seismologist's assessments of felt intensity have been criticised by engineers on a number of grounds. It has at some times been alleged that structures observed to have failed were 'not typical', and at other times that no account has been taken of some spectacular but isolated occurrence. The usefulness of the assessments has been questioned on the grounds that the scales used do not readily correlate with accelerations, or that no account is taken of the duration of the shaking. It has been alleged that differences in ground conditions are not taken into account, and also that they are, and that this should not be done. It has been objected that damage to poorly-built structures has been considered, and it has been stated that different intensities could be allotted if the effects of the earthquake were reconsidered 'in an engineering sense'.

Misconceptions of this kind are not found only among engineers who are facing the earthquake problem for the first time. The Report of the Japanese Earthquake Engineering Mission to Yugoslavia(2) contains the following statement: "The intensity of the earthquake in the most severely damaged area of Skoplje is estimated IX on the Modified Mercalli Intensity scale through Mission's observations on the damage to the brick buildings. However, from the observations on damage to bridges and underground pipes and on ground deformation, the intensity is estimated VIII or less on the same scale." The present conference affords an appropriate occasion to examine the nature of the intensity concept, and to discuss its usefulness at the present day.

THE PHYSICAL INTERPRETATION OF INTENSITY

Intensity is a measure of the effect of an earthquake upon natural objects, artificial structures, and human observers in a given locality. Where similar effects occur, the intensities are said to be equal; and where the effects differ, it is possible to place them in an order such that those characteristic of the lesser intensities are included in the greater. In practice, the number of categories of intensity that it is possible to distinguish is limited to about 12; and this accounts for the great similarity of all intensity scales that use this maximum number of degrees.

The concept of an intensity scale is an old one, and the number of scales that have been proposed very large. Davison[3] listed 27, and Gorshkov and Shenkareva[4] have attempted a correlation of no fewer than 44, the earliest of which was proposed in 1811 and the latest in 1956. Even this comprehensive list omits some important scales, such as Kawasumi's version of the Japanese scale[5]. Richter[6] has proposed a further modification of the widely-adopted Modified Mercalli scale[7]; and at the 1963 conference of the International Union of Geodesy and Geophysics held in Berkeley, California, general adoption of a scale devised by Medvedev, Sponheuer and Kárník was urged[8].

The scales most generally in use today derive from Cancani's proposals to the Second International Seismological Conference held in Strassburg in 1903[9]. Cancani appealed to two principles that have resulted in much subsequent confusion. The first is that an intensity scale should be capable of universal adoption, and the second that intensity can be and should be related to some instrumentally measurable property of the ground motion, such as the maximum acceleration.

Recent investigations with strong-motion accelerometers have directed attention to the complexity of the spectrum of the ground movement during an earthquake, and a full understanding of this complexity is necessary for rational structural design. At the same time, these investigations have tended to obscure the fact that at a given distance from an earthquake of a given energy (Richter magnitude), the movements of uniform bedrock are essentially similar, and most of the complexity results from the behaviour of the local sub-soil.

Assessment of the lowest felt intensities depends upon subjective human reactions. The objections to this have been adequately answered by Voigt and Byerly[10]. At the intensities in which the engineer is interested, the estimates depend almost entirely upon material happenings that can be objectively studied. More than one type of ground motion can destroy a building. The variable factors involved are the acceleration, the period, and the duration of the movement. Two of these factors, the duration and the period, depend upon distance from the origin of the shock, and this reveals itself as a branching of the intensity scale at low intensities, so that although some of the indications that establish a given degree of intensity are common to earthquakes of both near and of more distant origin, others will be found to apply only to small shocks of near origin, or to large earthquakes at greater distances, of which they are fringe effects. Richter[11] has drawn attention to this phenomenon, and Neumann[12] has shown that it continues to affect the relationship between intensity and acceleration at higher intensities.

This branching results mainly from change in period, and a dependence upon period must still persist at destructive intensities. However, at these intensities, the range of distances within which an earthquake large enough to produce them can occur is limited, and most observations relating to high intensities have been obtained from shocks at close range, and therefore with a restricted range of period and duration, assuming the ground conditions to be similar. This presumably explains why many engineers continue to press for an intensity scale with stated ranges of acceleration, possibly with some general stipulation about the period range within which the acceleration is to be measured.

Cancani's 1903 proposals were for 'a double scale, empirical and absolute', the absolute values being values of acceleration. These scales cannot both be fundamental. Either the felt intensities must be rough indications of intensity, since the two are not identical. It is not surprising that the accelerations Cancani assigned should since have been found unsatisfactory, but no one has been able to 'correct' them with any confidence. They were based upon work by Omori, Milne, and 'other famous seismologists' at the turn of the century, which suggested that an intensity of X on the Rossi-Forel scale then in use corresponded to an acceleration of 'not more than 2,500 mm/sec^2.' In view of the fact that 'in certain earthquakes in Japan and South America ground accelerations reached 10,000 mm/sec^2, Cancani proposed that the scale be extended to grades XI and XII. It should be noted that there was no intention to introduce a difference between the intensity grades on the new scale and the old, but only to extend it to include two additional grades of higher intensity.

Most English-speaking seismologists now employ the Modified Mercalli intensity scale in the form proposed by Wood and Neumann in 1931[7]. This scale leans heavily upon the German Mercalli-Sieberg scale[13], which is in its turn derived from Cancani. Wood and Neumann draw attention to the fact that they have omitted the acceleration limits assigned to the grades of the earlier scales. Although they make some general remarks upon the complexity of earthquake motions and the need to consider the duration of shaking, they give no explicit reasons for their decision.

Fig. 1 shows some of the relationships between intensity and acceleration that have been proposed. The Japanese intensity scales have been converted into MM ratings by assigning an appropriate MM figure to the effects listed as establishing their degrees. The discrepancies between these curves reflect the unsatisfactory nature of the measurements upon which they are based. Few observations are available at the highest or at the lowest intensities, and even at moderate intensities, the scatter is enormous. Hershberger[14], who examined 585 records of 189 earthquakes obtained by the United States Coast and Geodetic Survey notes that the highest acceleration attributed to MM 5 is more than 50 times the lowest.

It is instructive to look at these results the other way round, noting what consequences are to be expected from a given acceleration. According to Gutenberg and Richter(15), an acceleration of 100 $cm.sec^{-2}$ (approximately 0.1g) will produce an intensity of MM 10, which should destroy most masonry and frame structures, together with some well-built wooden buildings and bridges. Peterschmitt(16) and Kawasumi(17) are agreed that the intensity is about MM 7, and that the most that can be expected is that some damage to weak chimneys, loose brickwork, and unbraced parapets. The most inexperienced observer is unlikely to confuse these two sets of effects, and one is led to agree with Hershberger that "... this is not the way to arrive at any conclusion. The scatter of these results is too great to permit the assumption of any definite quantitative relationship between intensity and acceleration ..." The surprising thing about this conclusion is that it should have taken seismologists and engineers more than 50 years to reach it.

INSTRUMENTAL MEASUREMENT OF INTENSITY

If instruments that could measure the period and acceleration of the ground were available in sufficient numbers, it would be possible to dispense with the concept of intensity: but this is not so, and is never likely to be so. The radii of the felt areas of even moderate earthquakes are measured in hundreds of kilometres. In large shocks damage may take place at a hundred or more kilometres from the epicentre. The number of instruments required would therefore be enormous. It is consequently worth while to maintain a network of felt earthquake reporters, and to supplement their reports by issuing questionnaires and by undertaking field studies. The function of instrumental measurements is to enable these data to be interpreted in quantitative physical terms. Not only accelerations, but period, duration, and any other relevant physical quantities must also be measured.

A wide variety of strong-motion seismometers has been devised, ranging from three-component accelerometers with associated recording equipment of some complexity to simple sets of blocks that are assumed to be overthrown at certain accelerations calculated from their dimensions. Medvedev, Sponheuer, and Kárník(8) have proposed that the intensity scale should be formally linked to the response of one such instrument, a pendulum with a natural period of 0.25 sec. and a logarithmic decrement of 0.5. This requirement forms part of the Russian GEOFIAN scale proposed by Medvedev in 1953, and adopted as an All-Union Standard(17).

It is clear from the discussion of Fig. 1 that there is no present agreement upon what effects a given acceleration is likely to produce, and new information will force us to revise any suggested correspondence based upon the instrumental measurements now available. On the other hand, no new information can change an intensity rating based upon an accurate description of earthquake effects reported by a reliable observer. Proposals to link felt intensity scales to instrumental readings are therefore likely to destroy their precision, rather than to increase it.

New Zealand instrumental measurements of acceleration are few in number, and relate mainly to low intensities. Fig. 2 shows the relationship between MM intensities allocated by the Seismological Observatory, Wellington, and the accelerations recorded by instruments of various types operated by the Dominion Physical Laboratory (now the Physics and Engineering Laboratory) of the New Zealand Department of Scientific and Industrial Research. The data refer to 13 earthquakes between 1955 November and the end of 1961, for which accelerations were recorded at 17 different stations. Accelerations are appreciably higher than those suggested by Fig. 1, and this may be due to an association between the maximum acceleration and movements of short period. Whether this is the correct explanation or not, it is clear that under practical conditions, intensity can be estimated with greater certainty than can the acceleration necessary to produce a given set of observed effects. The inevitable complexity of the definition of intensity renders it unsuitable for direct instrumental measurement. While this remains the case, both the engineer and the seismologist will find uses for the concept of intensity.

THE REQUIREMENTS OF AN INTENSITY SCALE

The most important characteristics a scale should possess are that its degrees should be clearly distinguishable from one another, and that it should be a simple matter to observe the effects described. Thus 'Heavy furniture moved' is a good criterion; 'Rather strong shaking of houses' is not; and 'Felt only by an experienced observer' or 'Detected and recorded by seismographs only' are useless. It is also essential that any effect listed as typical of a given degree of intensity should always occur in association with the others listed for the same degree. For example, a scale that placed 'Small landslips in road cuttings' in the same degree as 'Vibration like a passing truck' would be suspect. It is also desirable that the scale should allot an intensity to all reasonably common happenings. It would be absurd if a scale for use in Japan did not include 'Overthrow of stone lanterns'; and to a New Zealander it seems odd that scales should ignore 'Cracking of earthenware toilet fittings.' Our overseas colleagues may insist that we should qualify this criterion by adding 'in wooden houses'.

The principal feature of Richter's modifications to the Mercalli scale[6] is an adequate clarification of the terms used to describe the quality of construction of buildings. The Wood-Neumann version and its predecessors employ such descriptions as 'ordinary substantial buildings', 'well-built ordinary buildings', and 'wood-frame houses built to withstand earthquakes'. Richter shows that some of these terms are inadequately translated from Sieberg's German, and that Sieberg had in mind certain Japanese buildings inadequately described by Milne. It is quite certain that the Mercalli scale does not refer to any structures built in accordance with the best modern anti-seismic codes. As building practices change, it is necessary to consider how they affect the description of the intensity scale. In New Zealand, for instance, the general incorporation of reinforcing rods in domestic chimneys is blurring the distinction between cracked chimneys (MM 7) and fall of chimneys (MM 8).

Wood and Neumann(7) criticise the Rossi-Forel scale on the grounds that 'it subdivides the intensity range unevenly'. This apparently means that they prefer a scale in which successive degrees are connected by the same mathematical law at all points of the scale. If Modified Mercalli intensities observed in an earthquake are plotted on a map and separated by isoseismal contours, it will be found that along any given radius from the epicentre, the spacing between successive contours is approximately constant. Gutenberg and Richter(15) show that 'for shocks at a given depth, successive isoseismals in a given range of distance have a definite spacing which is independent of the magnitude or energy of the shock, or of the epicentral intensity'. This conclusion is based upon the inverse square law of radiation (absorption being neglected), and an empirical (logarithmic) relationship between intensity and acceleration observed in a selection of Californian earthquakes. Relationships of this kind were used by Kövesligethy as long ago as 1900 for the investigation of focal depth, and came into general use when similar results were obtained by Gassmann(19). While it is undoubtedly convenient for such calculations that the scale should possess this kind of uniformity, it is by no means essential, and would be undesirable if it could be shown that any sacrifice of precision were entailed; for it is not necessary that the grades on the scale should be numbered with successive integers if the relationships between them can be precisely determined. It is of far greater importance that a given isoseismal, whatever combination of physical properties it represents, should be accurately and consistently located.

Any seismologist who has studied earthquake effects in the field will know that there are often certain striking criteria (not necessarily included in any intensity scale) that can be readily applied in a particular instance. In recent earthquakes in rural Northland, which occurred in the early hours of the morning, the boundary between the regions in which people were awakened and in which they were not was very sharply defined. This would not have been the case if the boundary had passed through a large city, or if the shock had occurred in the daytime. In a shock near Dannevirke, an equally sharp boundary existed at the outer limit of an area in which chimneys whose upper portions had been completely cracked through in an earlier shock had fallen to the ground. The fact that such an isoseismal does not coincide with a degree of any established scale does not lessen its usefulness.

Advocates of an international scale deprive the seismologist of criteria of this kind, without offering him any corresponding advantages. If the scale lists a wide enough range of effects to take account of the behaviour of Japanese lanterns, African mud huts, mediaeval cathedrals, and New Zealand wool sheds, the user in any particular country will have to select from the list the phenomena he can observe, and to reject the rest as irrelevant. In fact, each such seismologist will be using a different, though closely analagous, scale.

A persistent feature of intensity scales is the association of a single descriptive word with each degree of the scale. These terms range from the trite to the comic, and probably enshrine an unrealisable hope that the popular press will employ them consistently. For reasons of this kind, the Wood-Neumann version of the Modified Mercalli scale appeared in two forms, the 'abridged' form being 'adapted for the use of those who desire simply an outline of the principal features'. Unfortunately, the scale has been so often quoted in its shortened form that the fuller and more rigorous version is frequently overlooked. As Richter points out[20], the two versions conflict at some points, and it seems desirable to eliminate both descriptive words and abridgements from any new scale.

THE VALUE OF FELT INTENSITY OBSERVATIONS

If the focal coordinates and Richter magnitude of the earthquake are known, even a small number of felt intensity measurements have their value; but it is desirable to collect sufficient observations to enable isoseismal maps to be drawn and statistical inferences to be made. Isoseismals are customarily drawn so that they separate regions of different intensity, and the permissible degree of complexity of the curves depends upon the number and spacing of the observations. In New Zealand the average spacing of permanent reporters of felt intensity is about thirty or forty kilometres, but this is greatly reduced when special questionnaires are issued, as in the case of all earthquakes with a Richter magnitude of 6 or more, and other shocks of special interest.

When the area of earthquake damage includes a large city, as in the case of the 1906 San Francisco earthquake, it becomes possible to use intensities to investigate the effect of variations in sub-soil character. On that occasion, H.O. Wood examined every built-up block in the city, and assigned an intensity to each[24]. It would be quite impracticable to make such an investigation by instrumental means.

From isoseismal maps, it is possible to deduce the probable extent of damage in future earthquakes of similar magnitude, and to identify localities in which the intensities are commonly above or below those to be expected from considerations of distance from the origin of the shock. To the geophysicist, they have the further value that they throw light upon earthquake mechanism, and upon peculiarities of geological structure.

The fact that attempts to correlate intensity with acceleration and other physical quantities has failed does not lessen the value of systematic felt observations. Intensity information for a large number of earthquakes is available, and should repay study by engineers. The increasing number of strong-motion measurements should help in understanding these data, and increase rather than decrease their usefulness.

ACKNOWLEDGEMENTS

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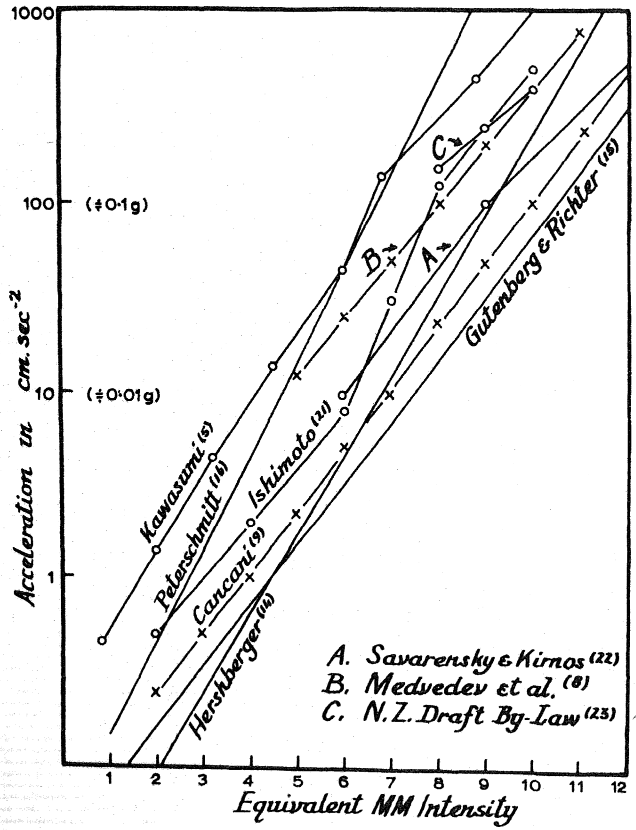

Fig. 1. Suggested Relationships between Ground Acceleration and Felt Intensity.

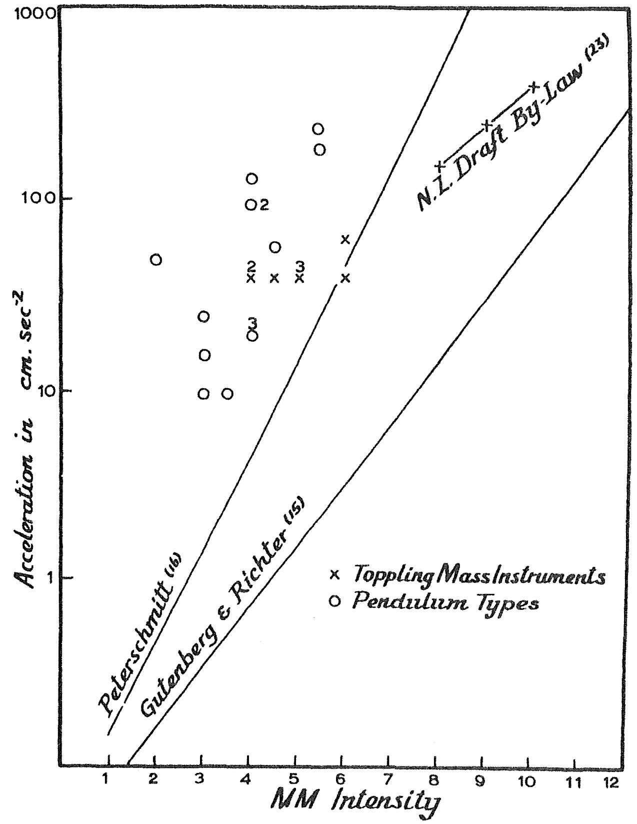

Fig. 2. Correlation between Felt Intensities and Measurements of Ground Acceleration made in New Zealand. Figures shown against the plotted points indicate a number of coincident observations. Three of the suggested relationships shown in Fig. 1 have been included to facilitate comparisons.

E R R A T A

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PAGE 64: paragraph 3, 3rd line: delete "Either the felt ..... not identical" replace by "Either the felt intensities must be rough indications of acceleration, or the accelerations must be rough indications of intensity, since the two are not identical".

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QUESTION BY: D.S. CARDER - U.S.A.

In comparing intensity v. acceleration the human element is very important. I refer to work by Hirshberger.

AUTHOR'S REPLY: The work of Hirshberger to which he draws attention is among my references. It establishes quite clearly that in the present state of the art, intensity is a quantity that can be more definitely established than acceleration.

QUESTION BY: O.A. GLOGAU - NEW ZEALAND

Mr. Eiby stated that in reporting such damage as that to chimneys which are relatively simple structures factors such as age, condition of construction type were important. Would he say that it was therefore necessary to carefully select the observers and that a qualified person such as a structural engineer was required if the information collected was to be meaningful?

AUTHOR'S REPLY: I do not think one needs to be a skilled structural engineer to tell a good chimney from a bad one. It is only in an extreme case that an intensity rating would depend upon the observation of a single chimney. The ratings must depend upon the whole complex of observed effects. At the highest intensities, where destruction to large buildings is involved, the help of a structural engineer would be very valuable, but not essential to an experienced seismologist. Some scientific training is certainly essential.

QUESTION BY: H. KAWASUMI - JAPAN

I have a different opinion from that of Dr. Eiby, because my statistical study in Japan shows a very good linear relation between the intensity and the logarithms of maximum accelerations observed by accelerometers.

AUTHOR'S REPLY: There is linearity for shocks at similar distances, but the absolute values assigned to a given intensity by different authors vary enormously.

QUESTION BY: **H.R. HALVERSON - U.S.A.**

What accelerograph characteristics do you consider to be of maximum importance?

AUTHOR'S REPLY: I do not think that seismoscopes giving only a maximum acceleration are satisfactory. The frequency spectrum of an earthquake is complex, and varies from shock to shock. Something might be done with a set of such instruments covering a range of periods, but I believe an instrument with a time-base to be essential.

QUESTION BY: **F.F. MAUTZ - U.S.A.**

Mr. Eiby stated two basic conclusions in his 9 point conclusion. 1. Some intensity measure scale by individuals is necessary. 2. Present intensity scales and methods of interpretation are inadequate and misleading as related to acceleration for engineering purposes. Shouldn't the engineering profession disassociate itself from any form of intensity scale or measurement where it may be related to accelerations such as has been recently attempted by some in the U.S. on a major project?

AUTHOR'S REPLY: At the present time, intensity data are more numerous and more reliable than values of acceleration. Reliable acceleration measurements should increase the value of these data. Concentration upon acceleration is diverting attention from significant variations in frequency spectrum and duration.