

## The INQUA Scale

### Definitions of intensity degrees

#### I, II No perceptible environmental effects

- a) Extremely rare occurrence of small effects detected only from instrumental observations, typically in the far field of strong earthquakes.

#### III No perceptible environmental effects

- a) Primary effects are absent.
- b) Extremely rare occurrence of small variations in water level in wells and/or the flow-rate of springs, typically in the far field of strong earthquakes.

#### IV No perceptible environmental effects

- a) Primary effects are absent.
- b) A very few cases of fine cracking at locations where lithology (e.g., loose alluvial deposits, saturated soils) and/or morphology (slopes or ridge crests) are most prone to this phenomenon.
- c) Rare occurrence of small variations in water level in wells and/or the flow-rate of springs.
- d) Extremely rare occurrence of small variations of chemical-physical properties of water and turbidity of water in lakes, springs and wells, especially within large karstic spring systems most prone to this phenomenon.
- e) Exceptionally, rocks may fall and small landslides may be (re)activated, along slopes where equilibrium is already very unstable, e.g. steep slopes and cuts, with loose or saturated soil.
- f) Extremely rare occurrence of karst vault collapses, which may result in the formation of sinkholes, where the water table is shallow within large karstic spring systems.
- g) Very rare temporary sea level changes in the far field of strong earthquakes.
- h) Tree limbs may shake.

#### V Marginal effects on the environment

- a) Primary effects are absent.
- b) A few cases of fine cracking at locations where lithology (e.g., loose alluvial deposits, saturated soils) and/or morphology (slopes or ridge crests) are most prone to this phenomenon.
- c) Extremely rare occurrence of significant variations in water level in wells and/or the flow-rate of springs.
- d) Rare occurrence of small variations of chemical-physical properties of water and turbidity of water in lakes, springs and wells.

- e) Rare small rockfalls, rare rotational landslides and slump earth flows, along slopes where equilibrium is unstable, e.g. steep slopes, with loose or saturated soil.
- f) Extremely rare cases of liquefaction (sand boil), small in size and in areas most prone to this phenomenon (highly susceptible, recent, alluvial and coastal deposits, shallow water table).
- g) Extremely rare occurrence of karst vault collapses, which may result in the formation of sinkholes, where the water table is shallow within large karstic spring systems.
- h) Occurrence of landslides under sea (lake) level in coastal areas.
- i) Rare temporary sea level changes in the far field of strong earthquakes.
- j) Tree limbs may shake.

## **VI Modest effects on the environment**

- a) Primary effects are absent.
- b) *Occasionally thin, millimetric, fractures are observed in loose alluvial deposits and/or saturated soils; along steep slopes or riverbanks they can be 1-2 cm wide. A few minor cracks develop in paved (asphalt / stone) roads.*
- c) Rare occurrence of significant variations in water level in wells and/or the flow-rate of springs.
- d) Rare occurrence of variations of chemical-physical properties of water and turbidity of water in lakes, springs and wells.
- e) Rockfalls and landslides up to ca. 10<sup>3</sup> m<sup>3</sup> can occur, especially where equilibrium is unstable, e.g. steep slopes and cuts, with loose / saturated soil, or weathered / fractured rocks. The area affected by them is usually less than 1 km<sup>2</sup>.
- f) *Rare cases of liquefaction (sand boil), small in size and in areas most prone to this phenomenon (highly susceptible, recent, alluvial and coastal deposits, shallow water table).*
- g) Extremely rare occurrence of karst vault collapses, which may result in the formation of sinkholes.
- h) Occurrence of landslides under sea level in coastal areas.
- i) Occasionally significant waves are generated in still waters.
- j) *In wooded areas, trees shake; a very few unstable limbs may break and fall, also depending on species and state of health.*

## **VII Appreciable effects on the environment**

- a) Primary effects observed very rarely. Limited surface faulting, with length of tens of meters and centimetric offset, may occur associated with volcano-tectonic earthquakes.
- b) *Fractures up to 5-10 cm wide are observed commonly in loose alluvial deposits and/or saturated soils; rarely in dry sand, sand-clay, and clay soil fractures up to 1 cm wide. Centimetric cracks common in paved (asphalt or stone) roads.*
- c) Rare occurrence of significant variations in water level in wells and/or the flow rate of springs. Very rarely, small springs may temporarily run dry or be activated.

- d) Quite common occurrence of variations of chemical-physical properties of water and turbidity of water in lakes, springs and wells.
- e) Scattered landslides occur in prone areas; where equilibrium is unstable (steep slopes of loose / saturated soils; rock falls on steep gorges, coastal cliffs) their size is sometimes significant ( $10^3 - 10^5 \text{ m}^3$ ); in dry sand, sand-clay, and clay soil, the volumes are usually up to  $100 \text{ m}^3$ . Ruptures, slides and falls may affect riverbanks and artificial embankments and excavations (e.g., road cuts, quarries) in loose sediment or weathered / fractured rock. The affected area is usually less than  $10 \text{ km}^2$ .
- f) *Rare cases of liquefaction, with sand boils up to 50 cm in diameter, in areas most prone to this phenomenon (highly susceptible, recent, alluvial and coastal deposits, shallow water table).*
- g) Possible collapse of karst vaults with the formation of sinkholes, even where the water table is deep.
- h) Occurrence of significant landslides under sea level in coastal areas.
- i) Waves may develop in still and running waters.
- j) In wooded areas, trees shake; several unstable branches may break and fall, also depending on species and state of health.

### **VIII Considerable effects on the environment**

- a) *Primary effects observed rarely. Ground ruptures (surface faulting) may develop, up to several hundred meters long, with offsets generally smaller than 5 cm, particularly for very shallow focus earthquakes, such as volcano-tectonic events. Tectonic subsidence or uplift of the ground surface with maximum values on the order of a few centimeters may occur.*
- b) *Fractures up to 25 - 50 cm wide are commonly observed in loose alluvial deposits and/or saturated soils; in rare cases fractures up to 1 cm can be observed in competent dry rocks. Decimetric cracks common in paved (asphalt or stone) roads, as well as small pressure undulations.*
- c) *Springs can change, generally temporarily, their flow-rate and/or elevation of outcrop. Some small springs may even run dry. Variations in water level are observed in wells.*
- d) *Water temperature often change in springs and/or wells. Water in lakes and rivers frequently becomes muddy, as well as in springs.*
- e) Small to moderate ( $10^3 - 10^5 \text{ m}^3$ ) landslides widespread in prone areas; rarely they can occur also on gentle slopes; where equilibrium is unstable (steep slopes of loose / saturated soils; rock falls on steep gorges, coastal cliffs) their size is sometimes large ( $10^5 - 10^6 \text{ m}^3$ ). Landslides can occasionally dam narrow valleys causing temporary or even permanent lakes. Ruptures, slides and falls affect riverbanks and artificial embankments and excavations (e.g., road cuts, quarries) in loose sediment or weathered / fractured rock. The affected area is usually less than  $100 \text{ km}^2$ .
- f) *Liquefaction may be frequent in the epicentral area, depending on local conditions; sand boils up to ca. 1 m in diameter; apparent water fountains in still waters; localised lateral spreading and settlements (subsidence up to ca. 30 cm), with fissuring parallel to waterfront areas (river banks, lakes, canals, seashores).*
- g) Karst vaults may collapse, forming sinkholes.
- h) Frequent occurrence of landslides under the sea level in coastal areas.
- i) Significant waves develop in still and running waters.

- j) *Trees shake vigorously; some branches or rarely even tree-trunks in very unstable equilibrium may break and fall.*
- k) *In dry areas, dust clouds may rise from the ground in the epicentral area.*

## IX Natural effects leave significant and permanent traces in the environment

- a) *Primary effects observed commonly. Ground ruptures (surface faulting) develop, up to a few km long, with offsets generally smaller than 10 - 20 cm. Tectonic subsidence or uplift of the ground surface with maximum values in the order of a few decimeters may occur.*
- b) *Fractures up to 50 - 100 cm wide are commonly observed in loose alluvial deposits and/or saturated soils; in competent rocks they can reach up to 10 cm. Significant cracks common in paved (asphalt or stone) roads, as well as small pressure undulations.*
- c) *Springs can change their flow-rate and/or elevation of outcrop to a considerable extent. Some small springs may even run dry. Variations in water level are observed in wells.*
- d) *Water temperature often change in springs and/or wells. Water in lakes and rivers frequently become muddy.*
- e) *Landsliding widespread in prone areas, also on gentle slopes; where equilibrium is unstable (steep slopes of loose / saturated soils; rock falls on steep gorges, coastal cliffs) their size is frequently large ( $10^5$  m<sup>3</sup>), sometimes very large ( $10^6$  m<sup>3</sup>). Landslides can dam narrow valleys causing temporary or even permanent lakes. Riverbanks, artificial embankments and excavations (e.g., road cuts, quarries) frequently collapse. The affected area is usually less than 1000 km<sup>2</sup>.*
- f) *Liquefaction and water upsurge are frequent; sand boils up to 3 m in diameter; apparent water fountains in still waters; frequent lateral spreading and settlements (subsidence of more than ca. 30 cm), with fissuring parallel to waterfront areas (river banks, lakes, canals, seashores).*
- g) *Karst vaults of relevant size collapse, forming sinkholes.*
- h) *Frequent large landslides under the sea level in coastal areas.*
- i) *Large waves develop in still and running waters. Small tsunamis may reach the coastal areas with tidal waves up to 50 - 100 cm high.*
- j) *Trees shake vigorously; branches or even tree-trunks in unstable equilibrium frequently break and fall.*
- k) *In dry areas dust clouds may rise from the ground.*
- l) *In the epicentral area, small stones may jump out of the ground, leaving typical imprints in soft soil.*

## X Environmental effects become dominant

- a) *Primary ruptures become leading. Ground ruptures (surface faulting) can extend for several tens of km, with offsets reaching 50 - 100 cm and more (up to ca. 1-2 m in case of reverse faulting and 3-4 m for normal faulting). Gravity grabens and elongated depressions develop; for very shallow focus earthquakes, such as volcano-tectonic events, rupture lengths might be much lower. Tectonic subsidence or uplift of the ground surface with maximum values in the order of few meters may occur.*

- b) *Large landslides and rock-falls ( $> 10^5 - 10^6 m^3$ ) are frequent, practically regardless to equilibrium state of the slopes, causing temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Levees and earth dams may even incur serious damage. The affected area is usually up to  $5000 km^2$ .*
- c) Many springs significantly change their flow-rate and/or elevation of outcrop. Some may run dry or disappear, generally temporarily. Variations in water level are observed in wells.
- d) Water temperature often change in springs and/or wells. Water in lakes and rivers frequently become muddy.
- e) *Open ground cracks up to more than 1 m wide are frequent, mainly in loose alluvial deposits and/or saturated soils; in competent rocks opening reach several decimeters. Wide cracks develop in paved (asphalt or stone) roads, as well as pressure undulations.*
- f) *Liquefaction, with water upsurge and soil compaction, may change the aspect of wide zones; sand volcanoes even more than 6 m in diameter; vertical subsidence even  $> 1m$ ; large and long fissures due to lateral spreading are common.*
- g) Large karst vaults collapse, forming great sinkholes.
- h) Frequent large landslides under the sea level in coastal areas.
- i) *Large waves develop in still and running waters, and crash violently into the shores. Running (rivers, canals) and still (lakes) waters may overflow from their beds. Tsunamis reach the coastal areas, with tidal waves up to a few meters high.*
- j) Trees shake vigorously; branches or even tree-trunks very frequently break and fall, if already in unstable equilibrium.
- k) In dry areas, dust clouds may rise from the ground.
- l) *Stones, even if well anchored in the soil, may jump out of the ground, leaving typical imprints in soft soil.*

## **XI Environmental effects become essential for intensity assessment**

- a) *Primary surface faulting can extend for several tens of km up to more than 100 km, accompanied by offsets reaching several meters. Gravity graben, elongated depressions and pressure ridges develop. Drainage lines can be seriously offset. Tectonic subsidence or uplift of the ground surface with maximum values in the order of numerous meters may occur.*
- b) *Large landslides and rock-falls ( $> 10^5 - 10^6 m^3$ ) are frequent, practically regardless to equilibrium state of the slopes, causing many temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Levees and earth dams incur serious damage. Significant landslides can occur at 200 – 300 km distance from the epicenter. Primary and secondary environmental effects can be observed over territory as large as  $10000 km^2$ .*
- c) Many springs significantly change their flow-rate and/or elevation of outcrop. Frequently, they may run dry or disappear altogether. Variations in water level are observed in wells.

- d) Water temperature often change in springs and/or wells. Water in lakes and rivers frequently becomes muddy.
- e) *Open ground cracks up to several meters wide are very frequent, mainly in loose alluvial deposits and/or saturated soils. In competent rocks they can reach 1 m. Very wide cracks develop in paved (asphalt or stone) roads, as well as large pressure undulations.*
- f) *Liquefaction changes the aspect of extensive zones of lowland, determining vertical subsidence possibly exceeding several meters, numerous large sand volcanoes, and severe lateral spreading features.*
- g) Very large karst vaults collapse, forming sinkholes
- h) Frequent large landslides under the sea level in coastal areas.
- i) *Large waves develop in still and running water, and crash violently into the shores. Running (rivers, canals) and still (lakes) waters may overflow from their beds. Tsunamis reach the coastal areas with tidal waves up to many meters high.*
- j) *Trees shake vigorously; many tree branches break and several whole trees are uprooted and fall.*
- k) In dry areas dust clouds may arise from the ground.
- l) *Stones and small boulders, even if well anchored in the soil, may jump out of the ground leaving typical imprints in soft soil.*

## **XII Environmental effects are now the only tool enabling intensity to be assessed**

- a) *Primary surface faulting can extend for several hundreds of km up to 1000 km, accompanied by offsets reaching several tens of meters. Gravity graben, elongated depressions and pressure ridges develop. Drainage lines can be seriously offset. Landscape and geomorphological changes induced by primary effects can attain extraordinary extent and size (typical examples are the uplift or subsidence of coastlines by several meters, appearance or disappearance from sight of significant landscape elements, rivers changing course, origination of waterfalls, formation or disappearance of lakes).*
- b) *Large landslides and rock-falls ( $> 10^5 - 10^6 \text{ m}^3$ ) are frequent, practically regardless to equilibrium state of the slopes, causing many temporary or permanent barrier lakes. River banks, artificial embankments, and sides of excavations typically collapse. Levees and earth dams incur serious damage. Significant landslides can occur at more than 200 – 300 km distance from the epicenter. Primary and secondary environmental effects can be observed over territory larger than 50000 km<sup>2</sup>.*
- c) Many springs significantly change their flow-rate and/or elevation of outcrop. Frequently, they may run dry or disappear altogether. Variations in water level are observed in wells.
- d) Water temperature often changes in springs and/or wells. Water in lakes and rivers frequently becomes muddy.
- e) *Ground open cracks are very frequent, up to one meter or more wide in the bedrock, up to more than 10 m wide in loose alluvial deposits and/or saturated soils. These may extend up to several kilometers in length.*
- f) *Liquefaction occurs over large areas and changes the morphology of extensive flat zones, determining vertical subsidence exceeding several meters, widespread large sand volcanoes, and extensive severe lateral spreading features.*
- g) Very large karst vaults collapse, forming sinkholes.
- h) Frequent very large landslides under the sea level in coastal areas.

- i) *Large waves develop in still and running water, and crash violently into the shores. Running (rivers, canals) and still (lakes) waters overflow from their beds; watercourses change the direction of flow. Tsunamis reach the coastal areas with tidal waves up to tens of meters high.*
- j) Trees shake vigorously; many tree branches break and many whole trees are uprooted and fall.
- k) In dry areas dust clouds may arise from the ground.
- l) *Even large boulders may jump out of the ground leaving typical imprints in soft soil.*

In the **Appendix 5** the draft of a field survey form is proposed, for collection of data and rapid intensity estimate during field recognition following the future earthquakes. Clearly, the field test of the proposed scale should be a major task in the next future.

### **Intensity - fault parameter relationships: discussion and conclusions**

Published empirical relationships between surface faulting parameters (i.e. rupture length, rupture area, rupture width, displacements) versus magnitude (e.g., Bonilla, 1978; Wells and Coppersmith, 1994), do not take into account dynamic parameters, notably stress drop, which varies versus fault length and slip type (cf. Mohammadioun and Serva, 2001). For instance, the systematic use, in the Wells and Coppersmith (1994) relation, of moment magnitude  $M$  (wherein stress drop is arbitrarily set at 30 bars) is liable to cause magnitudes to be either over- or underestimated. Accordingly, in order to assess the magnitudes of historical seismic events on the strength of paleoseismicity data, it is indispensable that rupture dynamics and the stress environment be taken into account. Recent paleoseismicity studies in the region of the San Andreas fault (Runkerstrom *et al.*, 2002) indicates that maximum displacement increases versus the depth of the seismogenic zone: displacement measured at the surface accordingly represents the lower limit of this parameters, and using it will unavoidably lead to an underestimation of magnitude.

The other primary effects of earthquakes (uplift and/or subsidence) are accounted for to a certain extent by relationships between magnitude and slip-rate (e.g., Slemmons and dePolo, 1986; Petersen and Wesnousky, 1995; Anderson *et al.*, 1996).

To date, there are no relationships linking primary ground effects and intensity. However, this connection is well evidenced in the description of the macroseismic scales for IX, X, XI, XII intensity degrees (see Table 1). We compiled new relationships using the data reported in Table 3 from a selected sample of crustal earthquakes. The data are plotted in Figure 4. We derived regression curves from the obtained values. This is a preliminary attempt that will be revised and updated by adding more detailed information on the earthquakes in Table 3, and including data from other surface faulting events.

We know that everybody can bring forward well-justified criticism concerning this approach, which we are willing to take into consideration. However, it is a fact that, within a given tectonic environment, intensity should increase if magnitude increases. It is entirely implausible that an earthquake of  $M = 6.5-7.0$  should produce the same intensity as a  $M = 7.5-8$  one. It is not physically correct, and macroseismic scales, if properly used, do not allow these values. Of course intensity XII, by definition, is where the scales saturate and therefore calls for professional judgment. In view of the preceding, the regressions in Figure 4 represent a very early stage of this endeavor. In fact, the purpose of publishing it is to provide a gentle provocation for the scientific community. We hope therefore that it will easily be proven false—but in the sense of Popper, 1934.

The use of ground effects for macroseismic intensity assessment is obviously affected by several uncertainties, as widely discussed in this paper. Most of the physical phenomena included in the proposed INQUA scale are relatively poor indicators of level, and should be considered carefully when used for intensity measurement. For the intensity levels lower than IX, the attempt of the INQUA scale is to bring environmental effects in line with the damage

indicators. In this range, the INQUA scale should be used along with the other scales. For this reason, we have included as Appendix 4 a set of comparative tables to allow a direct integration between most commonly used scales and the INQUA proposed scale. However, in the intensity range between X and XII the distribution and size of primary tectonic effects is arguably the most useful diagnostic of the intensity level. As suggested in the proposed INQUA scale, field observations on fault rupture length and surface displacement should be therefore consistently implemented in the macroseismic study of past and future earthquakes.