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SYNOPSIS Although induced seismicity associated with the impounding of reservoirs is a relatively rare phenomenon, it should nevertheless be taken into account, particularly in the design of dams located in aseismic zones.

The operation of dams is not significantly affected by induced activities: the main concern arises in situations where unexpected events might affect the behaviour of the construction due to soil liquefaction or might affect slope stability.

This paper reviews the principal elements which are considered to affect the occurrence of the phenomenon: the weight of the water storage, and the development of pore pressure under the storage. Both elements make differing contributions to the triggering conditions. The occurrence is related to special geological conditions difficult to evaluate but expressed mainly by the presence of brittle rock, as well as special fault conditions on occasion.

The model of induced seismicity is based on the idea of considering a newly-built reservoir as a new infiltration source. It assumes the development of an unsteady flow, with subsequent transmission of hydraulic pressure in the rock mass. This concept is applied in the paper to twenty case histories of the best known reservoirs at which induced seismicity was detected.

Associated seismicity may be induced by injections of waste fluids into rock, fluid extraction, deep mining excavations, underground nuclear explosions or most commonly by the impoundment of large reservoirs. Man-made earthquakes caused by the filling of reservoirs have drawn the attention of designers concerned with dam safety. The safety of dams, however, has rarely been jeopardized by associated seismicity - notwithstanding the destruction of the Koyna Dam in 1967. As a design problem, the matter became a supplementary hazard to the complex problem of safety and is usually connected to the impoundment, or sometimes to the operation of the reservoir. Filling may modify the behaviour of the storage area and in certain cases, a non-seismic area may be transformed into an area of seismic sources for a period of time. The necessity of evaluating the potential hazards of associated seismic activities is also dictated by the environmental impact and its implications for the risk analysis. The unintentional triggering of seismic activity at the Denver Arsenal (1965) as a consequence of injection of waste fluid should be considered as an example of maximum impact affecting the environment and the purpose of the project by ceasing the injections.

Associated seismic activity is more relevant to the development of water storages but it could be a potential hazard for other large man-made interferences with the state of stress in the earth crust. Examples of such major interferences are the use of geopressure and geothermal energy; the developments of major underground fluid reservoirs and the construction of dams and others.

As a basis the evaluation of the impact should include the idea of mitigation of the associated effects even though the triggering mechanisms are not fully explained. This entails only the development of reasonable procedure guidelines. The understanding of reservoir associated seismic activity has some implications in the study of natural earthquakes and it is part of the interest of the U.S. Geological Survey Earthquakes Hazard Reduction Program. A number of probabilistic approaches are used to evaluate the principal parameters involved in the triggering of the phenomena as well as the evaluation of the probability of occurrence of future developments, Idriss et al (1979). One such approach may be based on the use of existing collected data Simpson (1976) and Stuart-Alexander (1976). Using as probability expression, the ratio between the number of water storages associated with induced seismicity and the total number of reservoirs with induced seismicity and the total number of reservoirs with water depth exceeding 100m, points to a relationship between the magnitude of associated earthquakes and the volume of the storage (Fig. 1).

Reservoir associated earthquakes usually involve a relatively low level of seismicity, but about 15% of the known cases produced movements registering as high as 5 and 6 on the Richter scale. At the lower energy levels, small shocks of the same frequency occur and in several cases there is a correlation with water level changes. The incidence of the phenomena, when considering the first 25 deepest and largest capacity reservoirs, indicate that depth appears as more important (24%) than volume (16%). The probabilistic approaches have important implications in expliciting observations related to the incidence of the associated activities, which could thus generate more rational approaches for further evaluations. The evaluation of associated phenomena pertains as much to potential occurrence as the ascertaining of the effects on the dams.

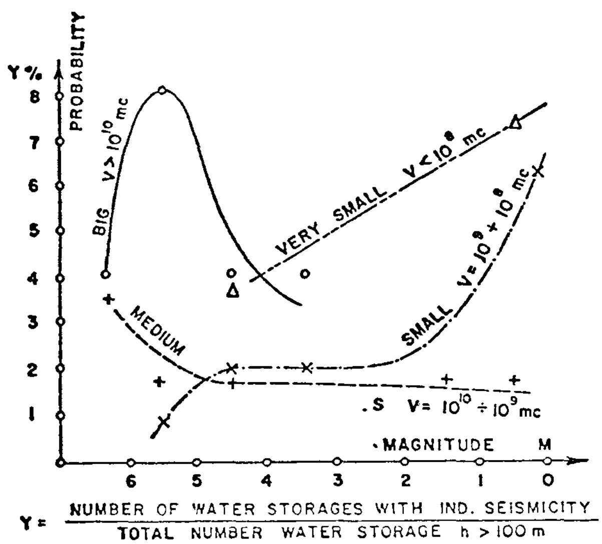


Fig. 1 Probability of occurrence of the induced seismicity related to the observed magnitude of the seismic motion. Y-probability of occurrence; M-magnitude.

A. EVALUATION OF THE OCCURRENCE OF RESERVOIR ASSOCIATED ACTIVITY

The evaluation of the hazard of reservoir associated phenomena is related to two different types of approach. The first consist in the comparison of empirical data, mostly drawn from geological sources, to elucidate the differences and similarities between proposed new reservoirs and known case histories of induced seismicity. The second approach uses theoretical patterns to investigate the triggering mechanisms of reservoir associated activities. Both approaches are important and could be integrated as a singular approach if the assessment of the geomechanical phenomena can be processed along the lines of geotechnical observational method.

The major difficulty in the correct application of the observational method is to ascertain the supposed main parameter as the major element and acquire the reliable observation data required to support the hypothesis of the principal element. Therefore, it is necessary to improve the geomechanical model by simplification and use the observation data to evaluate the comprehension and the validity of the pattern. It is a fact of life that often a more sophisticated model could be more easily elaborated, but the difficulty in corroborating it with field observation is generally increased. The application of the observational method can only be considered after a rather lengthy process of accumulation of observation elements. The author being in contact with the researchers in the field and this allowed the accumulation of data on reservoir associated seismicity, and the author is grateful to those of them who provided supplementary information by answering a questionnaire distributed with the help of different organizations (Canadian National Committee on Rock Mechanics, ICOLD, Water Power).

a) elements related to the mass of the reservoir expressed as storage depth and volume. The effects of the reservoir volume are quite variable and cover a large range between those of major reservoir of Kariba (10^{12} mc) and the small Camarilas Lake (4×10^7 mc). The range of the variation related to the depth is smaller, and is generally considered when depth is in excess of 100m. This orientative value has many exceptions. The minimal depth where associated activity is known is at the Almendra Lake in Spain with a depth of only 29m,

b) elements related to geological factors. The elements are very broad and often erratic. The presence of brittle rocks is considered a favourable condition for the triggering of seismic activity. In more general terms, the role of tectonic accidents seems to be subsidiary,

c) elements related to time development of the phenomena. The triggering of activity is closely related to the rate of filling. Variations in the degree of seismic activity occur over a considerable period of time after the impoundment (months,years). Quite often the associated activity is reduced to only a few major tremors.

A more recent approach to these observed elements is to consider that the filling of the reservoir and its consequences is the major source for the development of the associated seismicity. The filling of a reservoir was considered, Vladut (1980), as a new source of infiltration to the underground. There are several options in this approach, but all consider the filling as an unsteady source of flow. One of the simplified options is to consider the filling with the gradual transition of an unsaturated condition, and the modification of the water table over an extensive area. The modification in reservoir level which can be due to impoundment or operation, generate an unsteady flow and any hindrance of the flow will produce an increase in pore water pressure. The hindrance can be due to specific geological conditions or boundary conditions following the development of stresses and all the consequences such as reduction in hydraulic conductibility due to the increase of stresses. The differences between the different options are mainly the different theories concerning the flow through porous media to fissurated medium, as well as the different possibilities in expressing the soil parameters such as hydraulic conductivity and tensorial approaches such as fluid transmissibility. Improving the evaluation is done by better analysis of the field parameters such as fissuration, retention of fluid in the rock mass, generally through the use of models.

One such simple model is based on four major assumptions:

a) Considering the impoundment as an unsteady flow. The modification in the underground storage can be largely approximated as modifications in rock porosity (n) and fluid compressibility (ρ)

$$\frac{\partial}{\partial z}\left(Kzz\rho\,\frac{\partial h}{\partial z}\right) = \rho\,\frac{\partial h}{\partial t} + n\,\frac{\partial \rho}{\partial t}$$

b) The expression of changes in porosity using concepts of porous materials, is far from indicating the real behaviour of the rock mass affected by fissuration and different joints systems. Instead, the porosity change can be expressed in terms of deformability produced by the storage weight which affects a certain depth (H) under the reservoir (Fig. 2). Theoretically this affected depth is infinite but by common geotechnical approaches could be evaluated simply by accepting a supposed linear distributed of stresses along planes at 30 degrees, Hansen (1960).

c) To take into account the modifications of the storage levels, a simplified ideal morphology of the valley form was used. It was accepted that the parabolic form of valley could closely approximate field situations.

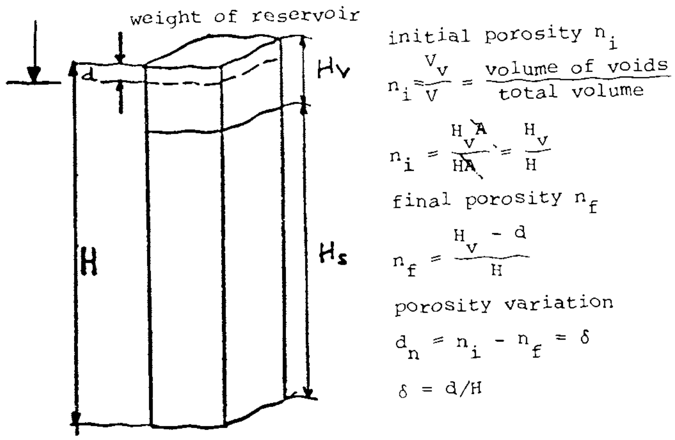


Fig. 2 Porosity variation under the reservoir weight.

d) Since the water level of the reservoir has annual variations, the unsteady development of the source is expressed as a sinusoidal variation. The flow spectrum would be obtained without using the initial conditions which are generally difficult to express, for example the transition from the unsaturated stage to the saturated condition. The impoundment could be approximated by the first increasing of the water level. The consequences of the flow can be represented by differences of stress developed (Fig. 3).

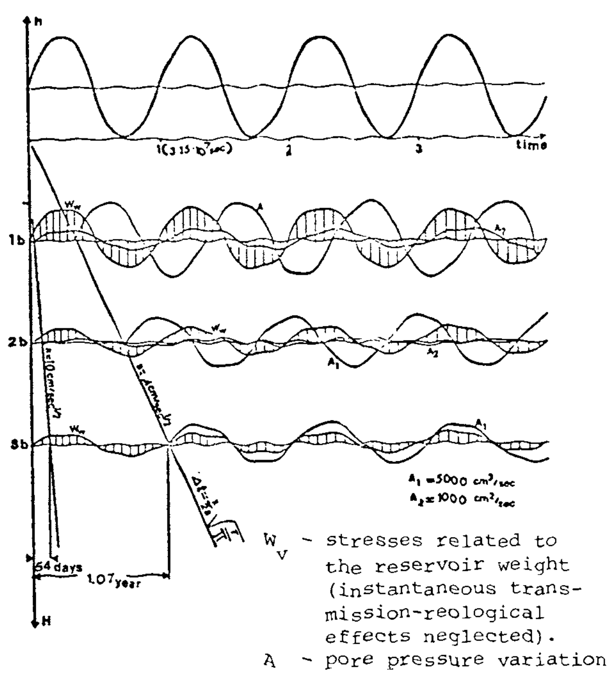


Fig. 3 Differences of stresses induced by the water level variations in the reservoir.

As a result of flow, differences of stress generated by weight modification and flow could in some conditions exceed the ultimate strength of rock. Particularly in a fissured medium, the tensile strength can be exceeded, thus inducing failure in the rock mass and consequently releasing the potential energy accumulated by the deformations under the storage weight, where the tensile strength is exceeded and failure develops this can be considered as the sources of microseismical activities. At the level of macroactivity this consideration is altered by the development of hindrances or other particular conditions on which the volume of the failure depends. The flow from the reservoir can be compared to the flow of water from a tank through an elastic pipe which is partially or completely blocked and the increase of pore pressure is akin to the force of flow inertia which could produce failure as hydrofracturation in the rock mass. In order to estimate the potential of induced modifications, the depth affected by the differences of stresses can be evaluated to give an indication of the potential of failure in the underground storage. The depth of the underground storage affected by the reservoir (H) can be calculated using a simple synthetic expression which is a primary corollary of Equation 1.

$$H = h\,\varnothing\,(\mu\ i\ \Theta) \qquad \text{Eq. 2}$$

where h - the height of the water in the storage at the time "t"; Ø - dimensionless number related to the product "Θi" representing the volume of the reservoir through its shape. The angle Θ is the aperture angle of the parabola which fit closely to the valley shape and "i" is the average slope along the theoretical parabolic reservoir, μ - Poisson's ratio of the rock mass. The representation of equation "2" (Fig. 4) is thus designed to encompass reservoirs with widely varying conditions. The constant contours of Ø are given to represent different rock conditions by different Poisson's ratio used as elastic parameters for the rock. The zone affected by the weight is larger for reservoirs resting on brittle rocks. There is consequently a significant increase in the depth (H) affected by the reservoir weight as the Poisson's ratio decreases. On the other hand, this depth decreases in the case of rocks with increased plastic components, where the Poisson coefficient is bigger. The effect of rock deformability as expressed by the Poisson's ratio is generally larger than the effect of reservoir geometry. Using the adimensional part of the depth (H) and the data collected on twenty reservoirs with reservoir induced seismicity, an area of occurrence can be outlined (the shadowed area on Fig. 4). This area is shown as an area with higher probability of encountering reservoir associated activity and is built up only using the field data. Besides outlining an area with higher probability of induced seismic occurrence, the adimensional diagram allows comparison between storage areas with different behaviours. The behaviour can be induced by taking into account the real variation of the water level in the storage area during impoundment or operations. The location of the motion source developed by the associated activity as hipocentre was obtained for only six reservoirs. The depths calculated with the flow model described above were compared with the known depths of hipocentres ascertained by instrumentation measurements and a good correspondence was obtained (Fig. 5). Following the same hypothesis, that the location of failures related to induced seismicity is in the range of depth affected by storage weight, the evaluation was extended for 20 cases which defined the area of increased probability. The uncertain element for both evaluations is the unknown real Poisson's ratio of the rock material. Using a wide range of Poisson's ratio between 0.1 and 0.4, the location of associated activity was identified as a shallow phenomena. The average depth was evaluated at 2.2 km which is close to the known field observation of induced activities. Some major exception can be found such as the Kremasta Reservoir with a deep hipocentre, about 18 km, and some very shallow activities at Schlegais, LG2 and other reservoirs.

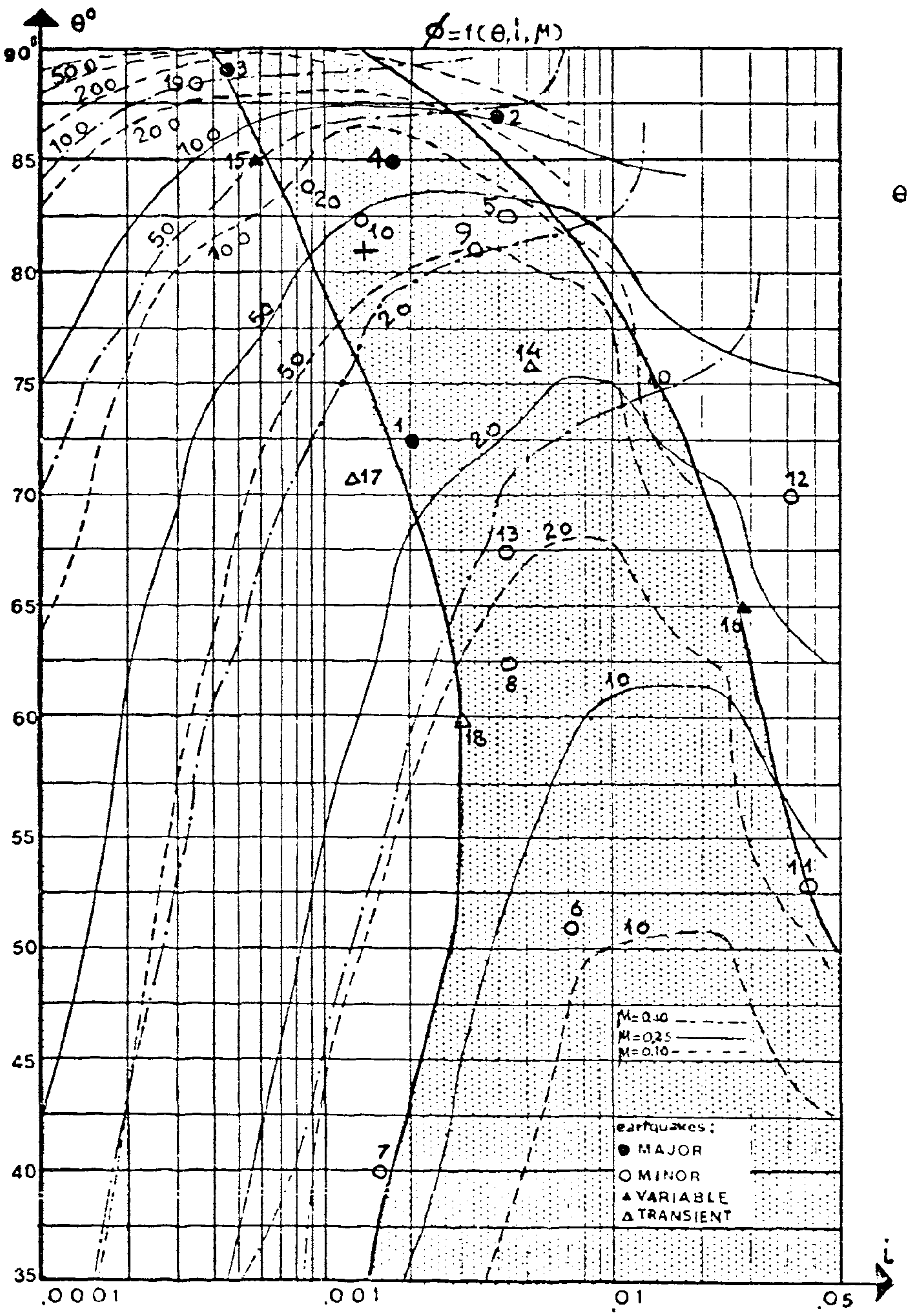


Fig. 4 Evaluation of the depth affected by the reservoir. Dimensionless number Ø.

θ Apperture angle of parabolic valleys.

i - slope along the reservoir.

– Poisson number of the rock mass.

H = hØ.

H - depth affected by the reservoir.

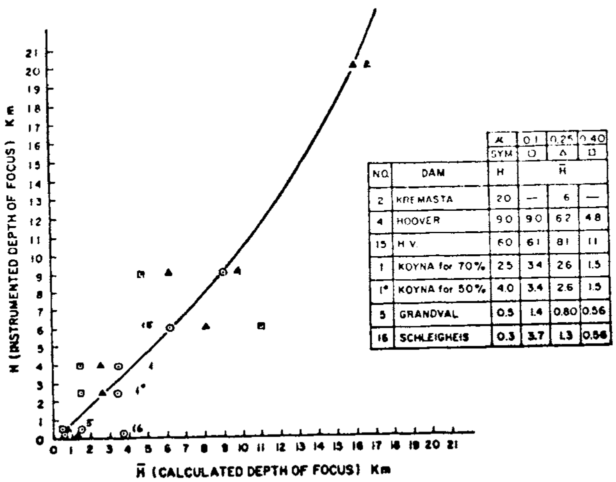
h - depth of water in the reservoir.

Pointed Zone: AREA OF OCCURRENCES of the induced seismicity for 20 reservoirs. The numbers indicate the name of the water storage:

1. KOYNA
2. KREMASTA
3. KARIBA
4. HOOVER
5. BENMORE
6. MONTEYNARD
7. BAJINA BASTA
8. NUREK
9. MANGALA
10. KEBAN
11. VAJONT
12. PIAVE DI CADORE
13. GRANDVAL
14. GRANCEAREVO
15. H. VORWOERD
16. SCHLEGEIS
17. QUED-FODDA
18. VOUGLANS
19. VOLTA
20. MANICOUGAN 3
21. LG 2 +

B. EVALUATION OF THE EFFECT OF ASSOCIATED SEISMICITY

The increasing need for the water as well as the imperatives for more economical solutions, impose that where the morphological situation allows, bigger reservoirs will be considered as the best solutions for water storages. The increase in depth of reservoirs induces the triggering of associated activities and the number of storages affected is increasing. For sometime this increase was mainly associated to concrete dams (gravity, arch). This is believed to be due to the state of the art practice which makes the construction time longer for earth dams than for concrete structures. The time difference is mainly due to the ceasing of construction activities during the winter time for most of the earth structures. This impression was generated by the fact that concrete structures were more common 15-20 years ago than earth dams for which increased developments are taking place for the last decade. Analyzing forty-two cases of water storage with associated seismicity the incidence of the phenomena is almost the same for each type of structure (Fig. 6). Then the risk incidence could be considered independent of the type of dam. The dam behaviour would be certainly evaluated by the response of the structure to dynamic stresses and where the material, as the type of structure, became conclusive. Generally the earthquake design of the structure is the expression of different concerns related to extreme conditions in which both stress and strength are modified. Both modified elements are affected by the evaluation of the magnitude of events such as ground motion especially acceleration, attenuation, duration and critical strength



		K	0.1	0.25	0.40
		SYM	O	Δ	□
NO	DAM	H	H̄		
2	KREMASTA	20	—	6	—
4	HOOVER	90	90	62	48
15	H V.	60	61	81	11
1	KOYNA for 70%	25	34	26	1.5
1*	KOYNA for 50%	4.0	3.4	2.6	1.5
5	GRANDVAL	0.5	1.4	0.80	0.56
16	SCHLEIGHEIS	0.3	3.7	1.3	0.56

Fig. 5 Evaluation of the depth of underground storage (H̄) and the hipocentre of induced seismic activities (H).

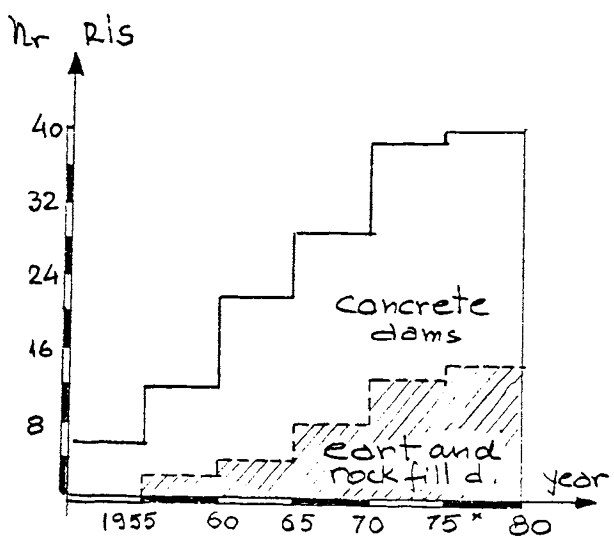


Fig. 6 Distribution of associated seismicity related to type of dams: earth and rockfill; concrete
* cases under study for RiS assessment not induced.

evaluation such as liquefaction, critical strains, etc.

When taking into consideration the associated seismicity effect, the basic difference with the natural activities, are their closer location to the dam structure and the relation with the water level variation. Using the pattern of development of associated activity given by the difference of stress generated by flow and weight, the effect of induced processes could be evaluated. This evaluation implies that failure developments in the rock mass is a consequence to the flow as a hydrofracturation which is different from the seismological approach of accepted elastic rebound theory where fault lines are basically the cause of seismicity. Thus one can evaluate the unexpressed degree of risk which is included in the design when no field investigation to evaluate the potential of induced seismicity was done. Indeed this could be used to build up some limits for the evaluation of the hazards. An approach of induced activity effect could be by the evaluation of the elastic energy stored through the rock mass in equivalent faulting. The actual field data available comes only from strong faulting motions. The few data collected is not relevant yet but it will continue further. The post motion deformations expressed by faulting are well documented and could be used for the evaluation of associated seismicity effects on dams through estimate of energy released. The area of magnitude under 7 on the Richter scale was investigated. The major induced seismicity are motions in the range of 6.5 on the Richter scale. The length of the equivalent rupture (L fault length) was evaluated through known relationships with the magnitude such as Tocher (1958) and Dambara (1980). The horizontal offset (D) was evaluated through the known King and Knopoff (1968) relation (Fig. 7). The elastic strain energy corresponding to the

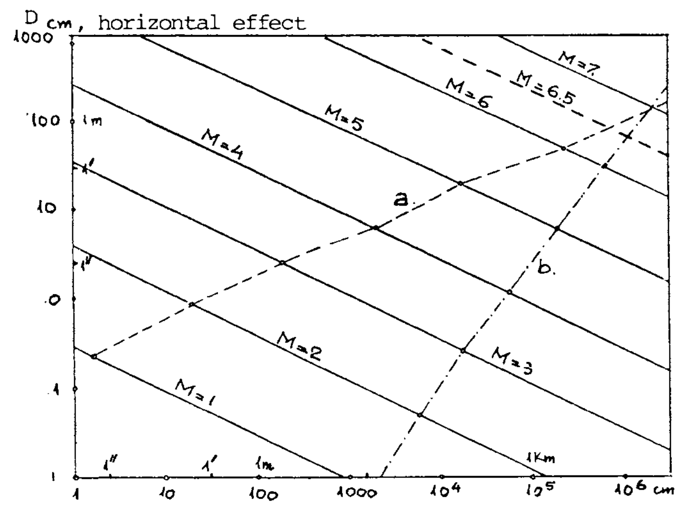


Fig. 7 Evaluation of fault dimensions related to motion strength:
King, K: $\log LD^2 = 1.9\ M - 2.65$
fault length relations:
a. D. Tocher: $\log L = 1.02M - 5.77$
b. T. Dambara: $M = 1.96\ L^2 + 4.45$.

evaluated faults was estimated as strain energy associated with the rupture through fundamental rock mechanical approximations, Jaeger and Cook (1969). The fracture corresponds to a specific difference between the strain energy of the fractured rock under specified stress and strain condition and the same body without the fracture. The comparison of this fault associated energy with the energy calculated with the elastic rebound theory such as the Gutenberg, Richter relation is quite close for specified stress-strain conditions. The energy differences (Fig. 8) could be explained by non-elastic behaviour, heat loss, etc. The discrepancy is bigger for small motions with a decreasing of the difference down to zero at the level of the maximum induced level (about 6.5). It should be mentioned that a Heimian stress distribution was used and low values of elastic parameters (MPa) should be used to minimize the discrepancy of energy. These low elastic parameters are somehow similar to Benioff's (1963) findings on low elastic stress present before earthquakes. The difference could be due to a lack of pertinent data about the intrinsic elastic constants of the rock and the effective elastic constants at the scale of the rock mass.

Reservoir associated activity should then be approached as any other rock failure and its consequences for dam

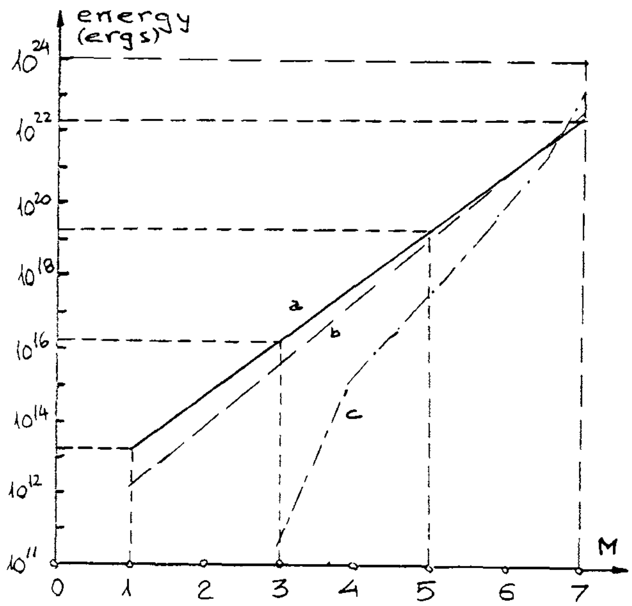


Fig. 8 Comparison of the released energy
a. Richter log E = 11.8 + 1.5M
Strain energy associated:
b. D. Tocher; c. T. Dambara

engineering. This comes as a complement to USCOLD conclusions Daly and Judd (1977), that the induced motions strength does not exceed the magnitude of natural earthquakes. In areas with a low natural earthquake-potential (M = 6), the presence of future reservoirs could imply risks of induced earthquakes with an upper bound at a magnitude 6 or 6.5 on the Richter scale. Thus associated sesimicity becomes important as a design consideration in areas of low natural earthquakes potential. In such areas the need to assess associated activities will become important especially if soils with liquefaction potential are encountered. The assessment of induced seismicity could become critical when linked to the attenuation aspects, in the evaluation of the most probable acceleration for shocks originating closer to the retaining structures. The duration and frequency of such induced activities will be finally dependent on the flow pattern which is a reservoir operation problem where often the impoundment is related to bigger gradients. Such operation problems can be expected with more frequency for pumped storages where level variations take place on a weekly basis.

The pattern of associated activities as a consequence of the induced difference of stresses generated by flow and weight could be useful in the actual design options choosing between dynamic overdesigning or assuming an unevaluated hazard factor related to an underevaluated risk. The proposed pattern is in the first approach and the induced differences of stresses could be evaluated in different ways. Improving the pattern will allow to elaborate some guidelines in reservoir impounding; velocity of filling in relation to tensional strength of the rock or a more complex passive antiseismic procedure. Nonetheless, the probability of evaluating associated motion related to storage level variations and rock properties also has scientific interest for many branches of the earth sciences.

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