PREDICTION OF INDUCED SEISMIC PHENOMENA RELATED TO RESERVOIRS

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ABSTRACT

A model of induced seismicity is proposed which considers the creation of a reservoir as a new source of infiltrations. It is suggested that an unsteady flow increases hydraulic pressure in the rock mass, and induces failure by creating a hammer-like water pressure at the boundary of the underground infiltration. This concept is applied to some of the better known cases of reservoir-associated earthquakes. It is pointed out that the proposed model might assist in the detection of geological conditions likely to trigger induced seismic activity.

The potential social and economic impact of seismic activity in populated areas makes the study and control of earthquakes an important scientific priority. Although the art of earthquake prediction is still in its infancy, the discovery that human actions may trigger serious earthquakes has provided an opportunity to increase our knowledge of seismic events.

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Seismicity may be induced by injections of waste fluids into rock (1), deep mining excavations, underground nuclear explosions, or most common by the impoundment of large reservoirs. Man-made earthquakes caused by the filling of reservoirs have drawn the attention of many researchers concerned with dam safety. The safety of dams, however, has rarely been jeopardized by induced seismicity -- notwithstanding the destruction of the Koyna Dam in 1967 with a loss of some 200 lives (2). An equally compelling reason for studying induced seismicity is the insight it provides into the behaviour of the earth's crust. A number of researchers -- notably those connected with the Rangeley experiment -- have pointed out that an understanding of induced seismicity has important implications for the study of natural earthquakes (3). This paper examines one approach to evaluating the conditions which could trigger induced seismicity in the course of reservoir impoundment.

It is difficult to ascertain the ways in which reservoir-associated earthquakes differ from those produced by fluid injections or mining activities. Attempts to distinguish between these phenomena have so far concentrated on the stress modifications induced by the weight of the loaded reservoirs (4). Attention has also been focussed on the depth and volume of the water storage, the character of the underlying rock forms, and the time lag after the filling of the storage area (5).

A number of probabilistic approaches may be used to evaluate the triggering of reservoirs. One such approach may be made by using the existing collected data (6) and expressed as a ratio between the number of water storages associated with induced seismicity and the total number of reservoirs with water depth exceeding 100 m. The occurrence of a seismic event could then be related to the storage volume and to the magnitude of the shock (Fig. 1). The usefulness of the probabilistic approach as a research tool lies in its ability to point out the main factors underlying induced seismicity. While this approach could have important theoretical implications, at the practical level it cannot generate procedures for avoiding or controlling man-made earthquakes.

A more fruitful way of approaching the problem is to study comparatively the triggering conditions in known cases of induced seismicity. Some 45 cases of reservoir-associated earthquakes have been recorded. The wide range of geomorphological conditions involved in these cases makes generalization exceedingly difficult, and Rothe's observations (5) remain important. One general condition, however, is applicable to all cases: the creation of a new water source through the filling of the reservoir (Fig. 2a) and the consequent increase of hydraulic pressure in the rock mass.

The filling of any reservoir produces changes in the water table over an extensive underground area, and voids will be saturated. After saturation, variations in the reservoir level generate a flow moving at a variable pressure toward the underground reservoir. Such filling of the reservoir creates an unsteady flow, which suggests the possibility that any hindrance of this flow will produce a significant increase in the pore water pressure. This hindrance would depend upon the specific geological conditions seen at the boundary of the reservoir -- e.g. a reduction in permeability due to a change in the type of rock -- or other modifications arising from the increase in stress. The flow from the reservoir to the boundary may be compared to the flow of water from a tank through an elastic pipe closed at one end, the increase of pore pressure resulting from the force of the flow's inertia. A sufficient concentration of such pressure in a rock mass may induce failure in the rock mass. It should therefore be possible to analyze the known cases of reservoir-associated seismicity by considering three aspects which could converge the stress levels at failure and to release the energy accumulated by deformation (7).

The first step is to consider the problem as one involving a linear unsteady flow. Modifications in the underground storage may then be expressed largely as modifications in rock porosity (n) and water compressibility (ρ) (Fig. 2a).

$$\frac{\partial}{\partial z}\left(K_{zz}\rho\frac{\partial h}{\partial z}\right) = \rho\frac{\partial n}{\partial t} + \frac{\partial \rho}{\partial t}n \qquad \text{"Eq. 1"}$$

The second step is to express the changes in rock porosity. The standard procedure for expressing such modifications is based on models of porour media behaviour (Biot theory, etc.). Yet the geological media most often encountered is a jointed rock mass which is far from porous. The author has therefore used a model f r porosity modification which takes better into account the behaviour of jointed rock. According to this model, porosity modification is expressed in terms of the surface deformability produced by the weight of the stored volume of water and the depth of the rock mass affected by the storage (Fig. 2b). The depth of the rock affected by the storage weight is theoretically infinite, but can be estimated by using a common geotechnical evaluation involving a linear distribution along planes inclined at thirty degrees (8).

The third step is to take into account the weight of the water storage as related to the unsteady modifications of the storage level. The volume of the storage is expressed as a function of the shape of the valley created by the reservoir. A simplified morphology of the valley is used as a parabola (Fig. 2c), and the volume is expressed in terms of the width of the reservoir, the aperture angle of the parabola θ, and the depth of the water in the reservoir expressed as a product between the length of the reservoir and the average slope along the water storage (i). Since the water level of the reservoir varied annually, the underground flow was considered to be a periodical variation (Fig. 3). This approach produces a flow spectrum without the use of initial conditions such as the transition from unsaturated to saturated stage. The flow generated is also a periodical movement dependent on variations in the reservoir level. Its amplitude decreases exponentially towards the interior of the underground storage and with a delay in direct ratio to the distance from the reservoir.

Important increments in pore water pressure might develop as a result of the unsteady flow at point arising from the difference between stresses induced by the weight of the reservoir and those generated by the flow. As a result the varying ultimate strengths of the rock --

particularly the tensile strengths -- may be exceeded at certain points, inducing failure in the rock mass and consequently releasing the potential energy accumulated by the deformations. Such points may be considered as the sources of the microseismical activities resulting from the rock failure. At the level of an earthquake, these considerations are altered only by the degree of hindrance on the boundary and other particular conditions on which the volume of the rock mass affected by failure depends. Theoretically a complete hindrance could induce a water hammer-like phenomena.

The depth of the underground storage affected by the reservoir (H) could be calculated using a simple expression which is a primary conclusion of Eq. 1 such as the following:

$$H = h\,\phi\,(\mu, i, \theta) \qquad \text{"Eq. 2"}$$

h - the height of the water level in the storage at time 't'; having an unsteady flow, it could be expressed by its variation in time dh/dt.

ϕ - dimensionless number related to the product "θi" which represent the volume of the reservoir.

μ - Poisson's ratio of the rock mass.

The representation (Fig. 4) of "Eq. 2" is thus designed to encompass reservoirs of widely varying geomorphological conditions. It is suggested, in confirmation of Rothe's observation (5), that the depth of the underground storage is strongly influenced by the deformability of the rock mass as expressed by brittle rocks which has a low Poisson's ratio. An area of occurrence of water storages associated with induced seismicity may be outlined in "Fig. 4".

In a study of 20 reservoirs associated with induced seismicity, the depths calculated by the above flow model were compared with the known depths of epicentres ascertained by instrumentation measurements. Unfortunately such measurements were available for only six of the reservoirs, and there was insufficient data of Poisson's ratio. Therefore engineering methods designed for situations involving uncertain data were employed to calculate the depths through almost the entire range of Poisson's ratio for all of the 20 reservoirs included in this study. A correlation was established throughout the range of variations of Poisson's ratio 0.1 to 0.4 to acknowledge the shallow locations of the focuses of induced activities with an average of 2.2 Km, and a close correspondence between the theoretical and field data was found (Fig. 5).

These results were used to predict the occurrence of induced seismicity connected with the impounding of reservoir L62 at James Bay, Quebec. The evaluation was based on a study of the occurrence areas of the reservoirs affected by induced seismicity (Fig. 4), and on the strength of the correspondence between the field data and calculations of the 'affecred depth' of the underground storage. During the filling of the reservoir, shocks registering between 1 and 2 on the Richter scale were recorded by the Earth Physics Branch of the Department of Energy, Mines and Resources.

A preliminary practical application of the above model is not related to the prediction of seismicity. It is the possibility of a feedback calculation of induced seismicity, starting from the instrumented seismological data, which could easily be checked against known variations in the level of the storage.

The ultimate goal of this paper, however, is to illustrate the uses of induced seismicity in improving our understanding of earthquake mechanisms. Such research ought to be considered as a complement to the major projects now under consideration for the control of seismic activity in the Mediterranean area (9) and along the San Andreas fault.

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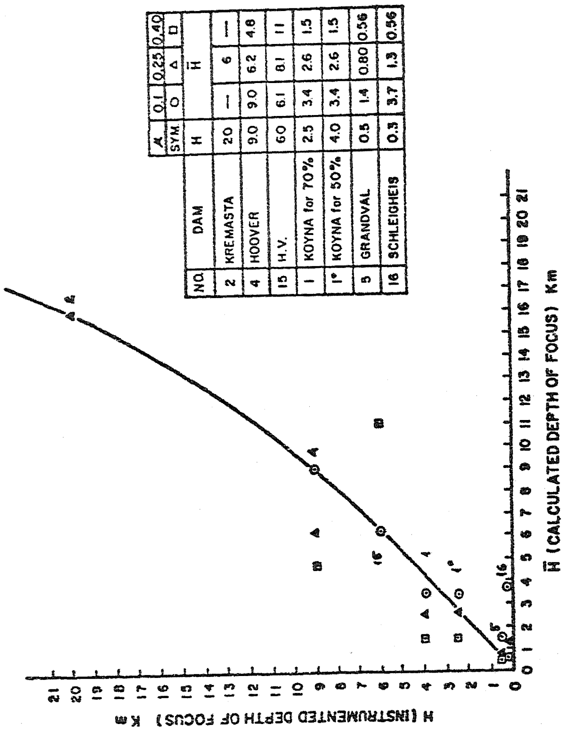
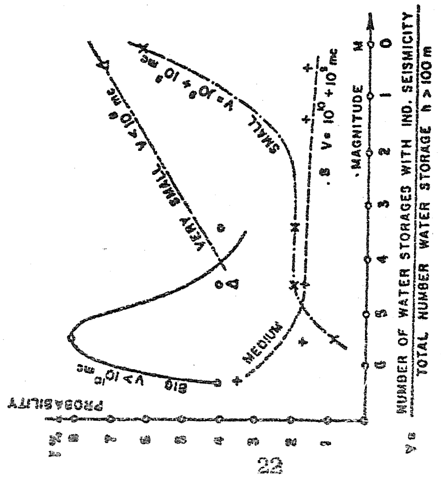


		λ	0.1	0.25	0.40
		SYM.	○	△	□
NO.	DAM	H	H̄		
2	KREMASTA	20	—	6	—
4	HOOVER	9.0	9.0	6.2	4.8
15	H.V.	60	6.1	8.1	11
1	KOYNA for 70%	2.5	3.4	2.6	1.5
1*	KOYNA for 50%	4.0	3.4	2.6	1.5
5	GRANDVAL	0.5	1.4	0.80	0.56
16	SCHLEIGHEIS	0.3	3.7	1.3	0.56

Fig. No. 5

Occurrence of the Induced Phenomena Related to the Observed Magnitude of the Seismic Event and Storage Volume.



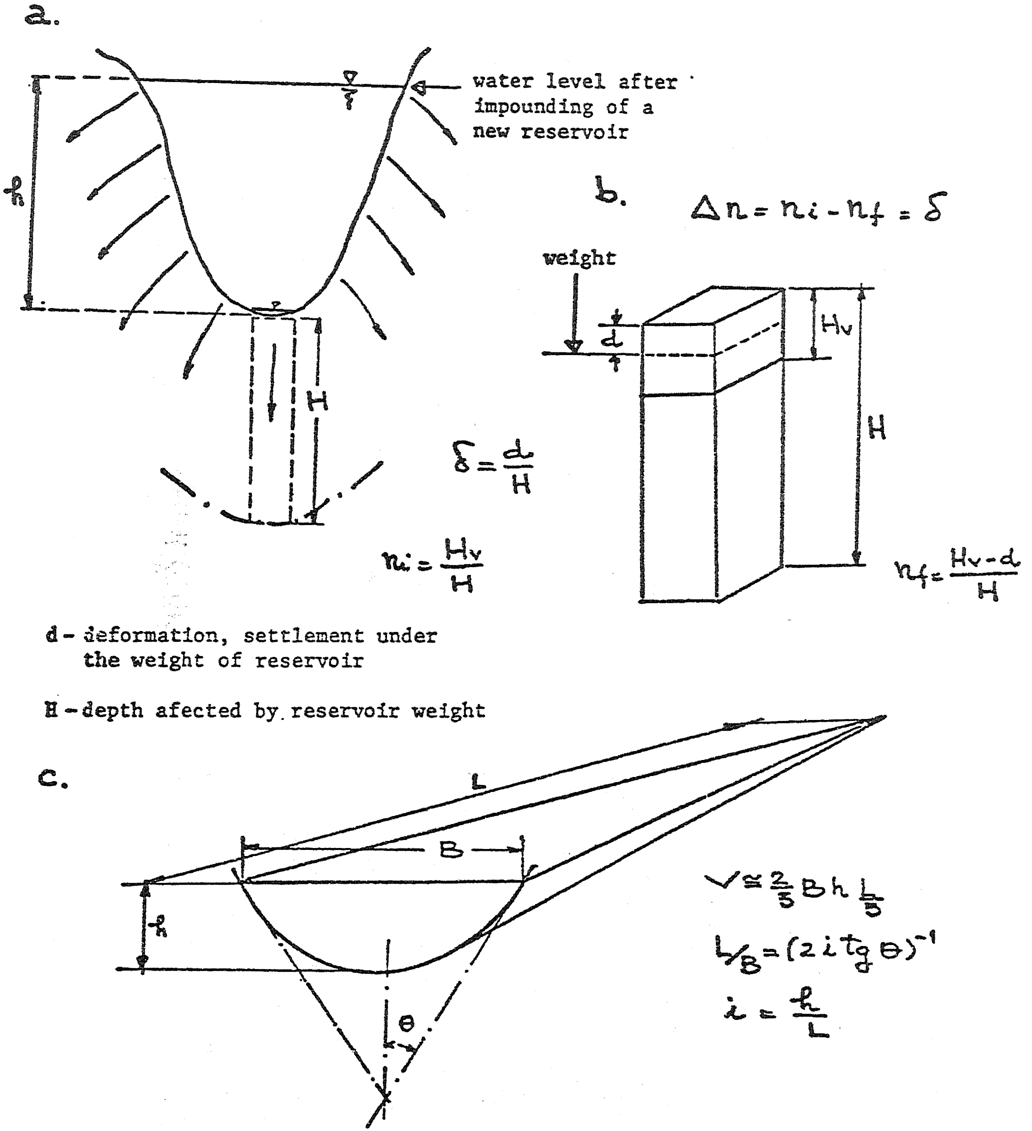
NUMBER OF WATER STORAGES WITH IND. SEISMICITY / TOTAL NUMBER WATER STORAGE h > 100 m

Y - Probability of Occurrence

M - Magnitude

Storage with V > 10^{10} mc - big
V = 10^{10} - 10^{9} mc - medium
V = 10^{9} - 10^{8} mc - small
V = 10^{8} mc - very small

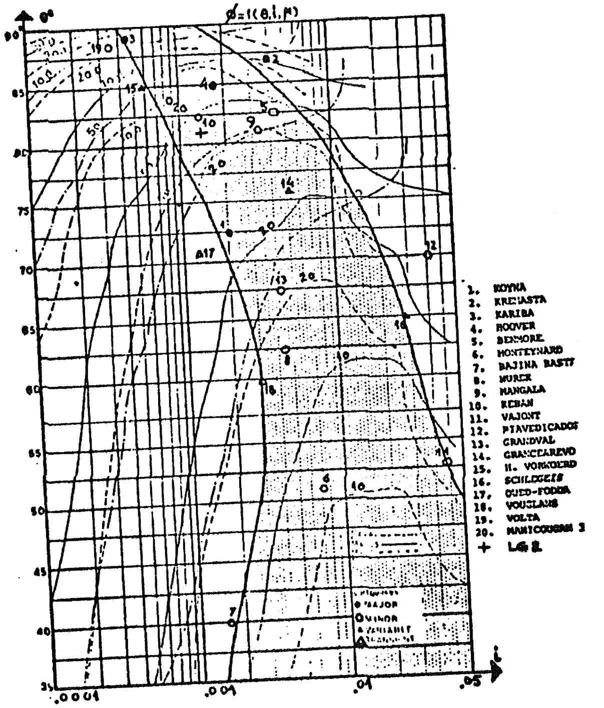
Fig. No. 1



d - deformation, settlement under the weight of reservoir

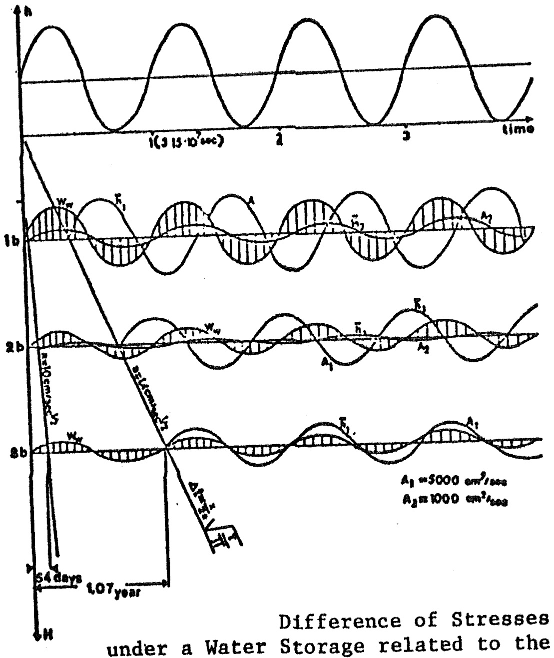
H - depth afected by reservoir weight

Fig. no. 2. Impounding of a new water storage modification -flow in the underground reservoir (a) and evaluations of "porosity" modification (b) and the volume of reservoir(c).



Relationship between Volume of the Water Storage (θ i) and dimensionless number of the depth of underground *storage* (ϕ) .

Fig. No. 4



Difference of Stresses under a Water Storage related to the Level variation in the Storage (h)

W_w - stress variation in the ground related only to the weight of water storage, A(h) = pore pressure variation.

Fig. No. 3