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RESERVOIR-TRIGGERED SEISMICITY: TWO CASE HISTORIES IN CENTRAL AND SOUTHERN ITALY

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EXTENDED ABSTRACT

I terremoti sono generati da movimenti tettonici della crosta terrestre; la coincidenza che alcuni siano stati generati, però, in seguito ad attività umane suggerisce che talora l'uomo può influire sulla loro genesi. Partendo dai dati di letteratura, soprattutto americana (Carder, 1970; Evans, 1966; Green, 1973; Gupta *et alii*, 1972; Gupta, 1992, 2005; Guha *et alii*, 1973; Hollister & WEIMER, 1968; ICOLD, 1998; Howells, 1973; OBORN, 1974; Okamoto, 1973; Munson, 1970; Muirhead *et alii*, 1973; Rothé, 1969; Snow, 1968; Scopel, 1970),, si richiamano i casi delle crisi sismiche di Mormanno (CS) del 2012 (INGV, 2016; Guerricchio, 1991, 2013; Guerricchio *et alii*, 1996), e di Amatrice (Appennino Centrale) del 2016, che potrebbero essere state indotte, almeno in parte, da bacini artificiali.

In letteratura non è nuovo il fenomeno di sismi indotti a seguito della realizzazione di bacini artificiali di estensione e volume significativi specie in zone simicamente attive; non mancano tuttavia esempi di terremoti indotti in bacini di dimensioni ridotte (ICOLD,1998).

E' intuitivo che tali eventi vanno attribuiti alla fratturazione idraulica lungo le superfici di faglia sottoposte in profondità, ad elevatissime pressioni interstiziali. L'azione meccanica di una faglia, infatti, "fracassa" la roccia, rendendola più facilmente permeabile ed erodibile. E' altresì arguibile, quindi, che l'acqua di un bacino artificiale ricadente su una faglia attiva filtra all'interno delle cataclasiti-miloniti della faglia e, sotto la pressione della colonna d'acqua sovrastante, innesca terremoti. Pertanto, va analizzata attentamente la sismicità naturale che può essere riattivata da sismi indotti dai cambiamenti di pressione dell'acqua sotterranea; essa, allontanando i labbri di una faglia ne fa diminuire l'attrito che contrasta il movimento, generando uno scorrimento improvviso con liberazione di energia meccanica sotto forma di onde elastiche.

Tra i casi di sviluppo o di riacutizzarsi di attività sismica ben documentati a seguito di costruzione di dighe ricordiamo i laghi Koyna (India), Kariba (Zambia), Kremasta (Grecia), Bileca (Yugoslavia), Talbingo (Australia), Mead e Cabin Creek (USA) e molte dighe in Giappone. Ciò può dipendere da:

a) aumento del carico verticale e depressione crostale circoscritta dall'acqua sovrapposta, e/o
b) filtrazione e/o aumento della pressione interstiziale lungo una potenziale rottura, con conseguente riduzione dello sforzo normale effettivo sulla superficie e una diminuzione della resistenza a taglio lungo di essa.

La condizione a) sarebbe improbabile per innescare il movimento a taglio del tipo scorrimento a scatti (*stick-slip*), a meno che la stabilità del sito fosse già critica prima del sovraccarico idrico. Per la condizione b), è noto che prima della rottura a taglio sotto una compressione isotropa (o idrostatica) una roccia all'inizio diminuisce di volume e quindi prima di rompersi, si dilata. Ciò porterebbe ad un aumento temporaneo di pressione interstiziale (favorevole al taglio) seguito da riduzioni della pressione dei pori (resistenza al taglio).

La più rilevante prova per a) deriva dall'evidenza nel campo petrolifero di Rangely (Colorado-U.S.A.) e dai successivi esperimenti di iniezione d'acqua (Snow, 1968; Hollister & Weimer, 1968; Scopel, 1970; Evans, 1966; Munson, 1970; Carder, 1970). Vi è in genere un certo ritardo tra il sovraccarico idrico e l'inizio di un'attività sismica significativa. Green (1973) riporta 6 mesi di ritardo nella diga di HendrikVerwoerde in Sud Africa. Howells (1973) ha usato la soluzione della equazione di diffusione unodimensionale per proporre che la pressione dei pori superficiale svolga attività determinante da 5 a 10 km di profondità dopo un centinaio di giorni e ad una profondità maggiore di 15 km dopo alcune centinaia di giorni. Tale sismicità è alquanto bassa inizialmente (7 km) ed è limitata alle vicinanze del serbatoio. Le rocce "plastiche" mostrano più sismicità temporanea delle fragili (Snow, 1972, Guha *et alii* (1873), Muirhead (1973) e Okamoto (1973).

Per maggiore conoscenza delle cause dettagliate di tale attività sismica Oborn (1974) confermava che la relazione tra velocità di sovraccarico idrico (*impounding*) e concentrazioni di sismicità è importante così com'è la velocità di costruzione di una diga in terra rispetto alle rotture a taglio per l'aumento della pressione dei pori. Le densità delle discontinuità meccaniche ("difetti delle rocce"), i giunti, la stratificazione, le faglie e le loro orientazioni nelle formazioni geologiche del sito di un serbatoio possono direttamente influire sull'attività sismica o meno; inoltre, in funzione della facilità di infiltrazione, i carichi più elevati di acqua ridurrebbero l'intervallo di tempo tra causa ed evento sismico. Pertanto, con tali premesse si sarebbe portati ad escludere paradossalmente l'esecuzione di importanti opere di sbarramento e di bacini artificiali, che però non è affatto il nostro auspicio.

ABSTRACT

Earthquakes are generated by tectonic movements of the Earth's crust. However, the fact that sometimes they occur with some man - related activities has suggested that their genesis may sometimes be affected by human action. On the basis of literature data, mainly from American studies, we report the cases of the 2012 earthquake crisis in Mormanno (Cosenza Province - Calabria Region) and that of 2016 in Amatrice (Central Italian Apennine), which can be considered, at least in part, as reservoir - related events. Both the basins fall in high tectonized areas with numerous faults which could condition water infiltration affecting interstitial pressures and earthquake development.

Keywords: *Induced earthquakes; Reservoir construction; 2010-2012 Mormanno earthquake crisis; 2016 Amatrice earthquake; Campotosto lake*

INTRODUCTION

In literature, the phenomenon of seismicity induced by large dam reservoirs, particularly in seismically active areas, is not new. While this phenomenon is more frequent in hundreds of meters deep reservoirs, or when their capacities are larger than 100 million cubic meters (ICOLD, 1998) (Tab. 1), there are also examples of induced earthquakes in smaller reservoir.

RESERVOIRS AND INDUCED SEISMICITY

It is intuitive that these events should be attributed to hydraulic cracking along the fault surfaces that are subjected to very high interstitial pressures at a few km of depth (Gupta *et alii*, 1972; ICOLD, 1998). The mechanical action of a fault, in fact, "crashes" the rock, making it more easily permeable and erodible, as in the case of deep valleys developing along faults.

It is also arguable that when reservoir, built on an active fault, is filled, water filters into the cataclastic - militonic material of the fault and, under the pressure of the overlying water column, triggers earthquakes with hypocenters even at kilometrical depths. Therefore, in the case of larger dams, it is essential to carefully analyze the natural seismicity in seismically active areas. Natural seismicity can be reactivated by earthquakes induced by pressure changes in ground water. It, can, for example, act on the two edges of a fault and reduces the friction that counteracts movement, generating a sudden sliding which release mechanical energy as elastic waves, i.e. the earthquake.

Basin	***Magnitude***	***Height of the dam (m)***
Koyna (India)	*6.5*	*103*
Kremasta (Greece)	*6.3*	*165*
Caribbean (Zimbabwe and Zambia)	*6.2*	*12*
Hsinfengkiang (China)	*6.1*	*105*
Orovile (USA)	*5.8*	*230*
Kurobe (Japan)	*4.9*	*186*
Nurek (Tajikistan)	*4.6*	*317*
Great Volta (Brazil)	*4.2*	*56*

Tab. 1 - Some reservoirs that induced seismicity, with its relative magnitude (after ICOLD, 1998)

Among the literature cases in which well documented dam related seismic activity in literature developed or exacerbated Koyna (India), Kariba (Zambia), Kremasta (Greece), Bileca (Yugoslavia), Talbingo (Australia), Mead and Cabin Creek (USA) lakes and a large number of other dams in Japan deserve to be mentioned. This may depend on:

a) an increase in vertical loading and crustal depression circumscribed by overlapping water, and/or
b) the filtration and/or increase in interstitial pressure along a potential breaking surface, resulting in a reduction in normal effective stress on the surface and a decrease of shear strength along it.

The condition a) by itself would be unlikely to trigger the sliding movement of the stick-slip type, unless the stability of the site was in a critical condition before the water overload. Looking at to condition b), it is known that before a cut break under isotropic (or hydrostatic) compression, a rock first decreases in volume and then, shortly before breaking, it dilates. This would lead to a temporary increase in interstitial pressure (favorable to the cut) followed by porous pressure reductions (shear resistance). But the most important demonstration for a) derives from the evidence given in the Rangely oil field (Colorado - USA) and by the subsequent experiments on water injection (Snow, 1968; Hollister & Weimer, 1968; Scopel, 1970; Evans, 1966; Munson, 1970; Carder, 1970) (Fig. 1). It can be noted that there is usually some delay between water overload and the beginning of significant seismic activity. For example, Green (1973) reports a 6 months delay in Hendrik Verwoerde Dam in South Africa. Howells (1973) used the solution of the one-dimensional diffusion equation to suggest that surface pores pressure plays a decisive role after a hundred days if depths range from 5 to 10 km, and after several hundred days at depths greater than 15 km. This seismic activity is initially rather low (7 km) and is limited to the immediate vicinity of the reservoir. The "plastic" rocks tend to show higher temporary seismicity than the fragile rocks (Snow, 1972; Guha *et alii*, 1873; Muirhead, 1973 and Okamoto, 1973).

For a better understanding of the detailed causes of this type of seismic activity, Oborn (1974) confirmed, for example, that the relationship between impounding speeds and seismic concentrations is important as well as the construction speed of an "earth" dam with respect to shear breaks by increased pore pressure. Densities of mechanical discontinuities ("rocks defects"), such as joint surfaces, stratification, faults and their orientations in the geological formations of the reservoir site can directly affect any development of the seismic activity; moreover, higher water loads infiltrate more easily, and this would reduce the time interval between the triggering cause and the seismic event. If the above data are considered, execution of important works such as dams and reservoirs, would be thus paradoxically excluded, but it is not our opinion.

EARTHQUAKES AND DAMS

The first detailed evidence of reservoir - induced effect occurred at the end of the 1930s when the Hoover dam (222 meters high) in the Mead Lake area (Colorado-USA), was impounded. The dam reservoir had a capacity of more than 35 Mm^3 (Fig. 1).

After 1936 local earthquakes became much more frequent and after the most violent earthquake the seismicity gradually decreased (Gupta & Rastogi, 1972).

During the first filling phase, that begun in 1935, an intense yet abnormal microsismic activity was recorded, which continued regularly for about 4 years, culminating on May 4/1939 in an event of M = 5, during the period when the reservoir reached its maximum capacity. Seismic activity continued and in the following 10 years there were about 6000 shocks of M <3 (Gupta & Rastogi, 1972).

The relationship between seismic activity and dam was clear,

Fig. 1 - Hoover Dam and Lake Mead (USA) on the Colorado River (222 meters high, basin with a capacity larger than 35 Mm^3. After construction, earthquakes, which were practically unknown in the area, increased and culminated in ‘39 with a magnitude M = 5 event (after Gupta & Rastogi, 1972). Coordinates: 39° 24’ 29.69”N -16° 35’97”E

given that no significant seismic activity had been detected since 1920, when the first seismograph was installed in the Mead area. From this first evident case, in 1969, the first research on induced seismicity was presented by P. Rothé in Santiago de Chile.

The work, greeted with skepticism by the scientific community, related the phenomena encountered in the Hoover Dam area with two other large dams: the Kariba Dam (Zambia / Zimbabwe) and the Koyna dam (India).

In the Kariba dam, located in the valley of Zambesi, which, up to that moment, was considered seismically stable, an abnormal microsismic activity was recorded during the very first filling phase, that in time grew by. In March 1962 only there were 63 earthquakes and 61 in the first 7 months of 1963; the U.S. Coast and Geodetic Survey calculated with certainty that at least 10 of them had their epicenter exactly under the reservoir. The basin filling was completed in 1963 and in that year there were two magnitude events of just over 6.0.

The Koyna dam (India) stands on the plateau of Deccan, one of the most stable seismic areas in the world; following the filling phase, intense microsismic activity occurred, culminating in a magnitude 6.2 earthquake in 1967, with 177 deaths and the injuries of another 2,300 (Gupta & Rastogi, 1972).

The maximum acceleration recorded in that event was 0.63 g, with epicenter near the dam; after the beginning of filling (1962), frequent shallow shocks began to be reported, located under the dam, in an almost aseismic area. The series of earthquakes shows a rhythmic pattern: by comparing the frequency of earthquakes and the water level of the dam that seismicity was reported to be greater several months after each rainy season, when the filling level is maximum (Fig. 2).

Next, similar reports have been produced for other large dams (over 100 meters) but only a few are well documented: although geological conditions vary from zone to zone, the most convincing examples of impounding - induced seismicity are reported in tectonic regions affected to some extent by previous seismic events.

UNESCO, following Rothé’s research, formed a working group that studied reservoir - induced seismicity; the group, between 1970 and 1974, reviewed a large number of cases and found that seismic activity was not only related to dam filling but also to dam emptying, such as for the Oroville dam (USA), or to the stability of the reservoir elevation. Most of the thousands of large dams on Earth, however, do not show any connection between reservoir filling and seismicity. Of the 500 large dams surveyed in the United States, in fact, only in 4% of cases there was an earthquake of M > 3 about 15 km from the dam (after ICOLD, 1998).

CAUSES OF DAM INDUCED EARTHQUAKES

It is difficult to believe that the main cause of reservoir induced earthquakes is just the effect of water overweight on the rocks; the actual pressure that is added in this way, just a few miles below the basin, is in fact only a small fraction of the natural tectonic effort already present (the additional effort is only a fraction of bar). A more plausible explanation is provided by the stimulation mechanism that produced the earthquakes of Denver and Rangely Oil Field (Snow, 1968).

The mechanism is probably the following: the additional water pressure produced by the overflow of the reservoir would propagate within the crust as a wave or pressure impulse, but its slow propagation speed may require months or years to travel 5 Km distance (depth), depending on the permeability and density of rocks fracturing (Howells, 1973). If the pressure impulse ultimately reaches a microfracture zone, it can force the water to penetrate through it and thus to decrease the forces preventing the existing tectonic deformation energy from starting the sliding and the elastic rebound along the faults.

Therefore, if a certain amount of elastic energy is accumulating along the fault, when a fluid is injected along it, an earthquake knock occurs.

Recent experiments have shown that by injecting or extracting fluids in deep wells, it is possible to turn on or off the seismic activity (seismic switch) (after ICOLD, 1998).

WATER EFFECT ON EARTHQUAKES

If there was no water in the rocks, no tectonic earthquakes would occur. There are several reasons: first, the pressure at a depth of 5 km within the earth's crust (due to the weight of the overlying rocks) is equal to the resistance of the granite (or a similar rock). Therefore the pressure it can withstand without breaking is approximately 1000 bar at a temperature of roughly 500°C, suitable values for that depth.

At higher depths, given that the lithostatic pressure is higher than the resistance of the rocks, we might expect them to slide and plastically deform, rather than break, giving rise to sudden fractures (which generate earthquakes).

In fact, by submitting a rigid granite sample to compression laboratory tests at suitable temperature and pressure conditions, it deforms plastically without breaking; it may thus paradoxical that the earthquakes occur. Leaving laboratory tests apart, seismic wave recordings of real earthquakes, when the focus is superficial (where groundwater exists) the shear strain along the faults abruptly decreases by a few dozens to several hundred of bars. These stress decreases are modest and much lower than the strength of the stone rocks reaching up to 1 kbar; it is therefore plausible that water along the fault zones weakens them and they release only a small amount of shear strain during the seismic event. Water would thus induce a sudden dislocation, probably producing a kind of "lubrication" along the sliding surfaces.

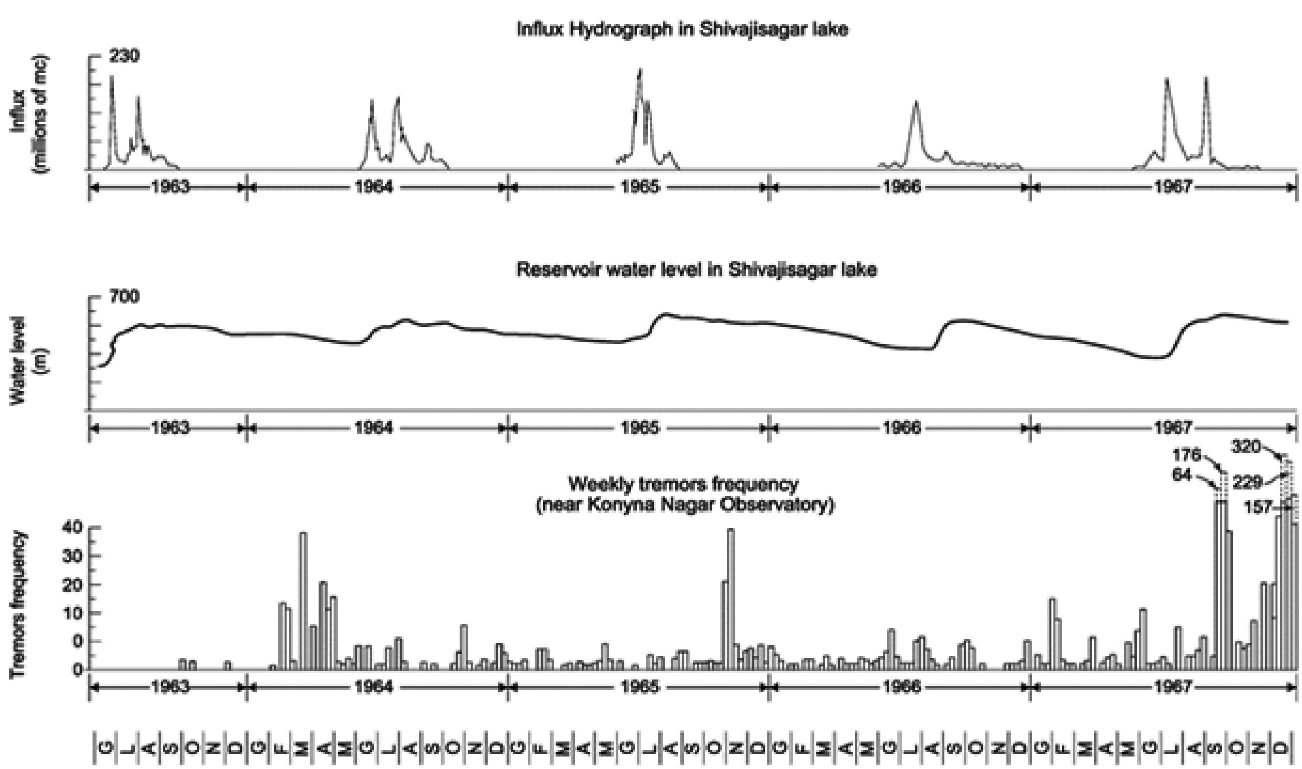

Fig. 2 - Koyna Dam in India. Correlation between the water level in the basin and local seismic activity. In the months of September, October, November and December 1967 the frequency of shocks exceeded 40, and sometimes, by the end of the year, it rose to 200 or 300. (after Gupta & Rastogi, 1972)

In laboratory tests, dislocations generated in rock samples depend on the crushing press, they are related to sudden pressure reduction; that is, every stress implies a nearly instantaneous reduction of the strain on the sliding surface (i.e. the fault in the geological reality) inside the sample.

Other evidences exist that water may have an effect on the mechanisms of earthquakes; note that in the fault zones there are fault debris, i.e. crushed and deformed rocks, and clays (cataclasites and milonites) containing water, as shown by transverse sliding (slickensides) associated with wet conditions.

Following the first case in Hoover Dam relating water to earthquake generation, seismologists focused their attention on a series of earthquakes that occurred in Denver (Colorado) in 1962 (Fig. 3). Though an event of the seventh degree of the Mercalli Modified Scale was recorded in 1882, natural seismicity there had been always low in the area. The situation suddenly changed in April 1962 and September 1963.

More than 700 earth tremors with epicenters in the area were recorded, their magnitude ranging from 0.7 to 4.3 Richter, within a radius of 8 km from the Rocky Mountains Arsenal (NE of Denver). In the area, American army produced armaments, and needed large quantities of water, that was initially collected in surface tanks to evaporate, and was then injected under pressure in oil wells, in a 12,045 feet deep basin of granite and pre-Cambrian gneissic rocks. These were very fractured and very permeable; there were 610 shocks, 18 of which had Richter magnitudes from 3 on.

Denver residents protested for a possible correlation between pumping and earthquakes, until they succeded to stop that draining water method. Two possible explanations of these effects are plausible:

- The increase in water pressure in the well caused a flood inside of tectonic discontinuities (cracks and fractures in pre - existing underground faults); such an increase in pressure in the pores caused a decrease in the strength of the shear strains of rocks and detritic materials (cataclasites).
- Due to the fracturing conditions of the rocks in the existing fault zones, a flow of water would occur in preferential directions along microfractures and fault surfaces; this interstitial water would have produced an important “lubrication” effect.

These conditions could have induced relaxation of the crustal tectonic deformations (accumulated over the decades) through a series of dislocations producing earthquakes. This relaxation of tectonic deformations probably would not have occurred for several years, or not in such a short period, if no additional water pressure had been introduced.

Data from the Denver case were accidentally obtained, and field experiments were designed to reproduce similar conditions.

Works began in 1969, by USGS, at Rangely Oil Field in the western Colorado region. At that time numerous oil wells were already available through which injecting or extracting water

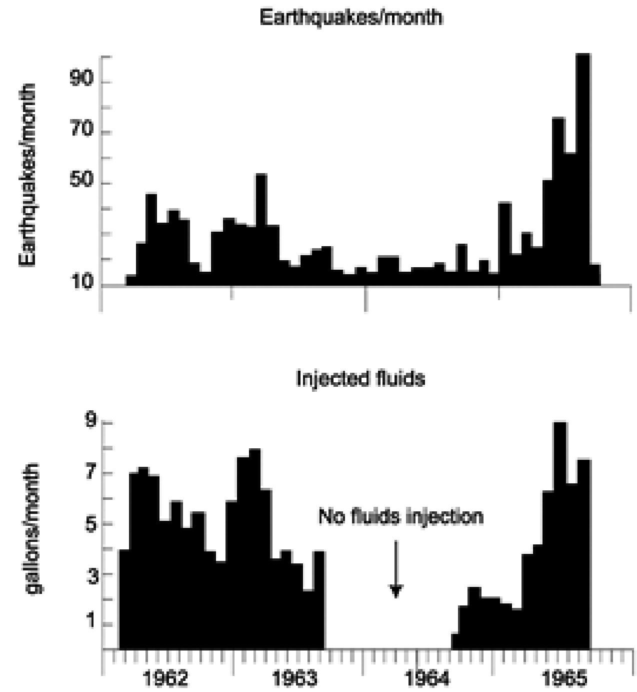

Fig. 3 - Denver (Colorado). There is a clear correlation between the amount of injected water and the number of earthquakes in the period between 1962 and 1965. It can be noted that in early 1963 there was a high frequency of local earthquakes followed by a marked decrease in 1964 and then by another rich series of earthquakes in 1965, when the amount of injected water, due to increased pumping pressure, was again at its maximum (after USGS)

with regularity by measuring the pressure in the rock pores.

At the same time, a seismograph network was set up, suitably located, in order to detect fluctuations in local seismic activity (Fig. 4). The results showed an exceptional correlation between the amount of injected fluid and local seismic activity (after USGS).

When the fluid pressure in the pores reached a level of threshold of 1.1x104 Pa (i.e. 260 kg/cm^2), seismic activity increased, when it decreased, as a result of water extraction, the seismic activity decreased as well (Fig. 4). It should be noted that the Rangely wells crossed preexisting faults and that the crust in that region was already affected by tectonic deformations, as can be deduced from the moderate local earthquakes occurring occasionally in previous years.

Denver and Rangely Oil Fields studies thus showed that water is of fundamental importance in causing sudden fractures deep in the crust. Such studies have also implied earthquakes can be in some way controlled.

REVIEW OF RECENT SEISMIC CRISES IN ITALY

After the reported world experiences, may be possible to conjecture about the recent or very recent seismic crises recorded

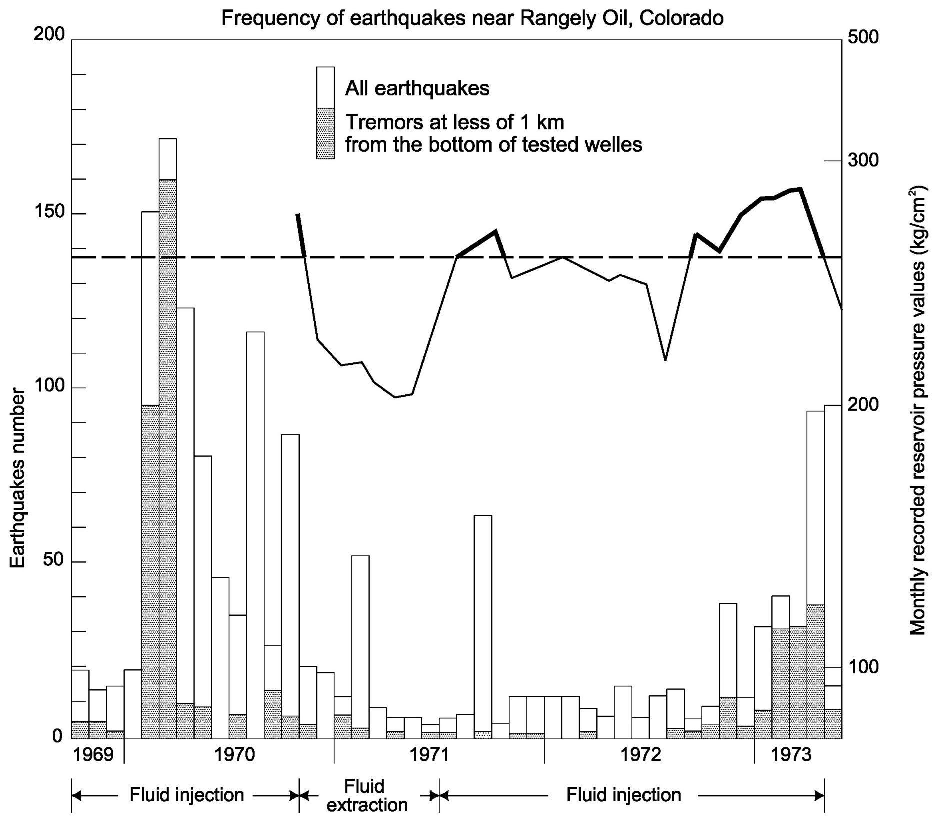

Fig. 4 - Frequency of earthquakes at Rangely Oil Field (Colorado) during an experiment in which the water was alternately pumped in and out of the wells. Tank pressure is traced as a continuous line. The pressure threshold required to trigger earthquakes is 260 kg/cm[2] (dashed line). Those that were below this threshold were due to natural causes. Each vertical column represents the number of earthquakes that occurred each month of their respective years (after USGS)

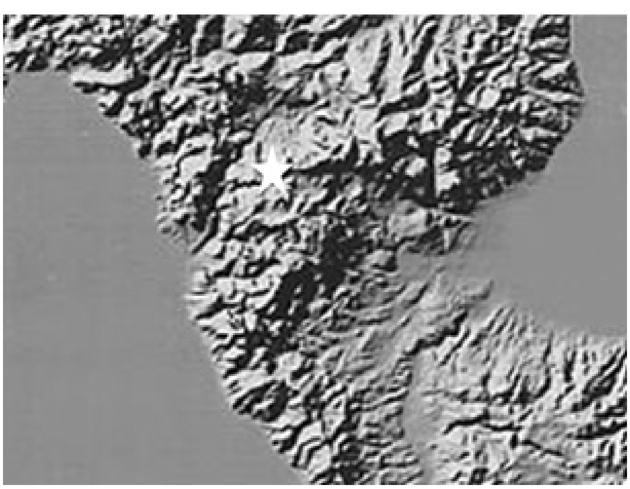

Fig. 5 - DEM of Northern Calabria, which shows dense large scale tectonic fracturing, in a very complex geological context, where the town of Mormanno (star) and the reservoir fall; it is evident therefore that the basin is located in a very permeable area. Coordinates: 40° 08'09.95"N15°28'02.04"E;39°52'29.48"N16°54'23.29"E;39°20'58.85"N16°31'53.72"E;39°36'10.07"N 15°23'37.03"E

in our territory, that of Mormanno in Calabria (Cosenza province) in 2010-2013 and that of Amatrice (Central Apennines) in August 2016. Reservoirs are present in both areas, though with very different characteristics. They are both located in active fault areas where lake waters have deeply penetrated in the past years, causing the "lubrication" phenomenon mentioned above. However, the hypothesis is difficult to quantify.

MORMANNO

From DEM and satellite imageries (Figs 5 and 6) one can observe the dense large scale tectonic fracturing in Northern Calabria area, where the town of Mormanno stands (star). In this very complex geological context, about thirty years ago a reservoir was built for hydroelectric purposes just a short distance from the inhabited area, in the upper part of the BattendieroTorrent (Fig. 7). On October 26, 2012, after a seismic swarm lasting many months, the event of M = 5.2 was recorded. Local people still remember the event of January 8, 1693 evaluated by the INGV at the VIII degree of the Mercalli scale. Basically, even though the Mormanno Lake is of a modest size, the permeability of the cataclastic dolomitic rocks

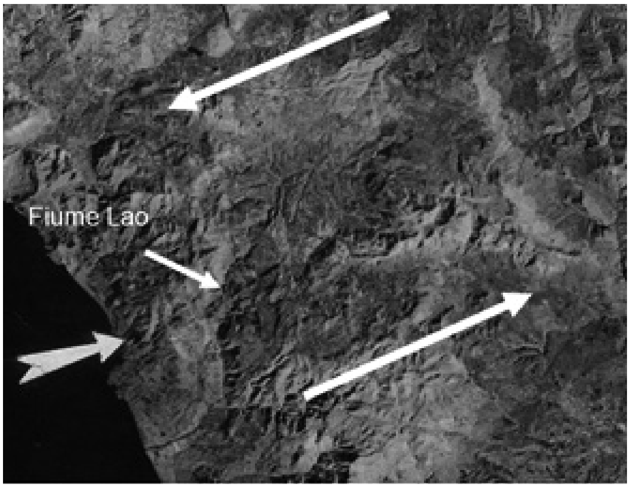

Fig. 6 - The northwestern portion of M.t Pollino Chain, involved in a "vortex" movement generated by a couple of strains (or moments of forces), was also involved in the further tectonic geomorphic upheaval of the territory including Mormanno, and increased the permeability of stone soils and other soils as well (after Guerricchio*, 1991). Coordinates: 39°48'12.08"N-15°41'45.10"E; 39°41'26.10"N- 16°17'18.71"E*

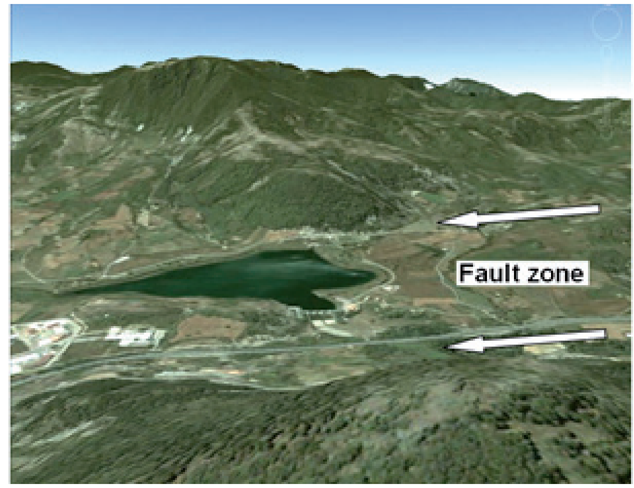

Fig. 7 - The artificial reservoir created by a "dam-crossing" in the middle-high portion of the Battendiero River, near the town of Mormanno (CS), along an active regional fault. The lacustrine basin falls along a regional fault directed W-E, which involves, in particular, limestone and dolomite rocks which outcrop in a cataclastic facies. Coordinates: 39° 52' 50.26" N - 16° 00' 18.24" E; 39°52'39.90" N – 15° 59'38.82"; 39°52'14.40"N – 16°00'59.58"E; 39°51'58.06" N – 15°59'38.85" E

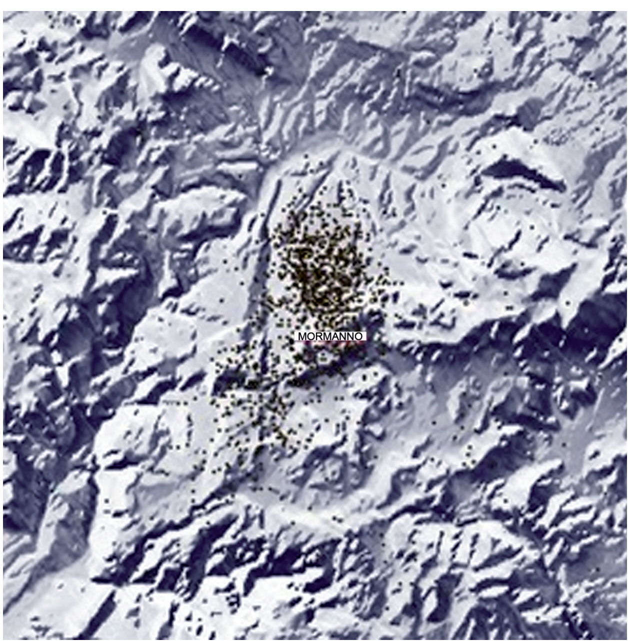

Fig. 8 - DTM of Northern Calabrian area, with location of the epicenters of prevalent low magnitudes in Mormanno and Coppola di Paola-il Cappellazzo area (after INGV). Most of those recorded in the Mormanno area from 2010, suggest that their genesis may derive from the re-triggering of snap movements in the structures associated with the "whirl", or the re-mobilization of the numerous ancient DSGDs in the area, triggered and favored by surface water infiltrations from even small reservoirs (after INGV). Coordinates: 39° 46' 30.76" N-15° 49' 44. 73"E;39°47'17.52" N-16°13"18.21"E; 40°02' 55.60"N-16°10'25.37"E;40°0.1'01.02"N-15°44'54.00"E

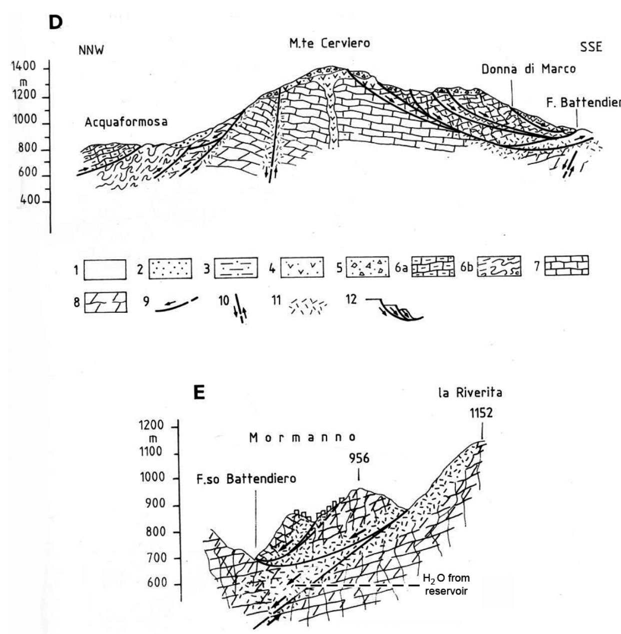

Fig. 9 - Geological sections showing the conditions of strong permeability of the limestone-dolomitic rocks of the Mormanno area-M. Cerviero. It should be considered that the Lake is located less than 1 km from the town, in very permeable cataclastic dolomite rocks, involving DSGSDs (7, 8, 11 and 12 in legend) at the intersection between the Praia-Pollino regional fault and that of the Battendiero Stream (after Guerricchio *et alii, 1996)*

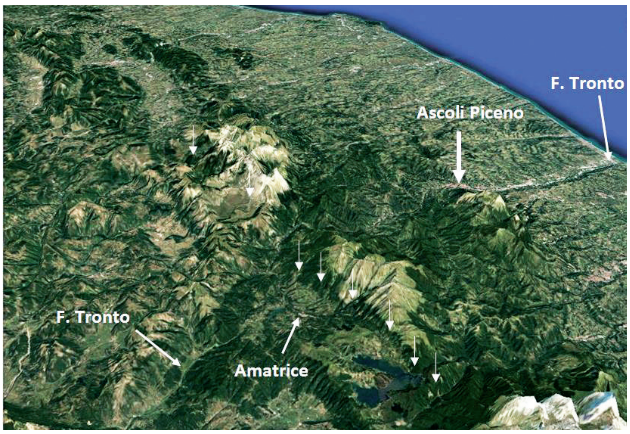

Fig. 10 - Apennine Front, with Campotosto Lake (Southward of Amatrice) and the long seismogenic fault (arrows) of the Amatrice earthquakes. Coordinates: 42°33'04.67"N-12°58'42.49"E;42°25'21.71'N-13°34'21.04"E;43°25'10.37"N-14°14'02.74"E;43°47'57.66"N-12°51'36.98"E

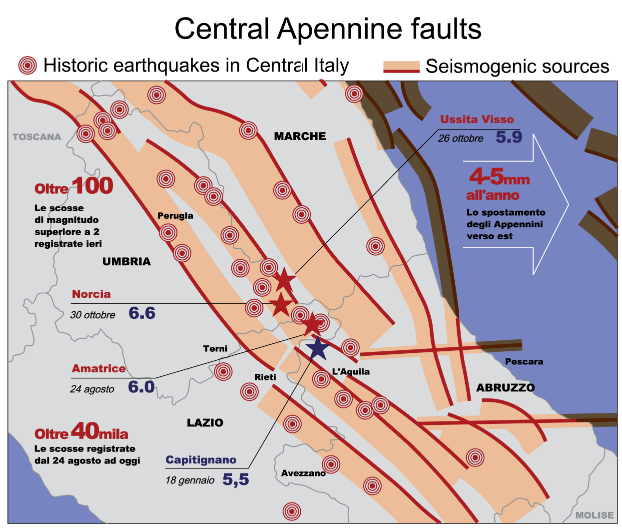

Fig. 11 - Synthetic picture of the major faults involved in the seismic crisis of the Central Apennine from August 2016 onwards and location (between the Amatrice and Capitignano stars) of Lake Campotosto (data after the INGV, reworked by La Repubblica, 26th August 2017 and by the author)

of the site (Fig. 9) has allowed the waters to drain deeply, and. in a very long time, it "lubricated" the "fault" of the BattendieroTorrent and its tributaries. The seismic crisis was triggered, almost certainly as a consequence of the above mechanisms. The lake, among other things, has caused groundwater level to rise throughout its upstream catchment.

AMATRICE

The territory including the towns of Amatrice, Campotosto, etc. subsided because of a NNW - SSE regional fault (Figs. 10 and 11) located at the foot of a Trias-Jurassic dolomitic - calcareous

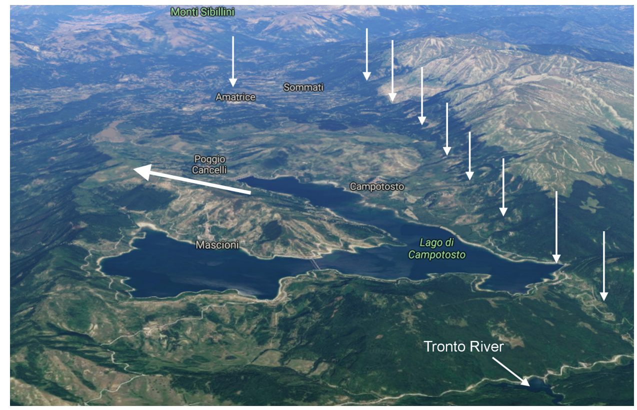

Fig. 12 - Image of the Campotosto Lake crossed by a first seismogenic fault (arrows) as well as by a second one, antithetical to of the first, which runs on the eastern side of the relief from the arched ridge, to the base, at the foot of which the two lake branches of the lake develop. It is as if this last structure had been expelled (oblique arrow) to the west as a result of the "sinking" of the marly - arenaceous Miocene formation (big vertical arrow). Coordinates: 42°27'17.74"N 13°19'21.77"E; 42°30'34.36"N 13°32'48.67"E; 42°48'22.25"N 13°30'06.68"E; 42°38'57.74"N 13°06'24.24"E

structure that culminates near Campotosto in Mount di Mezzo (2136 m). It connects the carbonate structure with the Marly - Arenaceous Formation of the Medium-Lower Miocene, that forms the entire Amatrice territory. The sunkening (an ancient "settling") has induced the uplifting or rather the expulsion of a number of reliefs including Colle Macchia Mozza, Colle della Serra, etc., which appear to be convexely arched towards WSW (Figs. 10 and 12). The fault completely cuts Lake Campotosto at the dam, follows a NW - SE direction between Mount Piano (1710 m) to NE and Mount Castellano (1517 m) to SW (Figgs. 10, 11, 12 and 13), where it forms a more than 400 m deep depressed ridge between the two R. la Collina reliefs with a width of more than 1 km. It was in this geological-geomorphological context that the lake of Campotosto was created in the middle of the last century, by damming the Rio Fucino, a left tributary of the Tronto River; in this same intermountain plain area, a late Pleistocene lake basin once stood (Figs 10, 12 and 13). The present basin covers an area of 14 km^2, a reservoir capacity of 163 million m^3 and includes the towns of Capitignano, Amatrice and Norcia, three of the sites destroyed or severely damaged by the recent shocks. Moreover, it lays along a few kilometer long stretch of the seismogenetic fault. As mentioned above, the soils in the area consist of sandy clayey marles, arenaceous and limestone marls, scailed, debris limestones and marl limestones, etc., which apparently provide a good impermeability.

However, the presence of the mentioned fault makes the contact areas between of the Limestone-dolomite structures and those of Marly - arenaceus structures particularly permeable. It is therefore reasonable to associate the recent earthquakes recorded

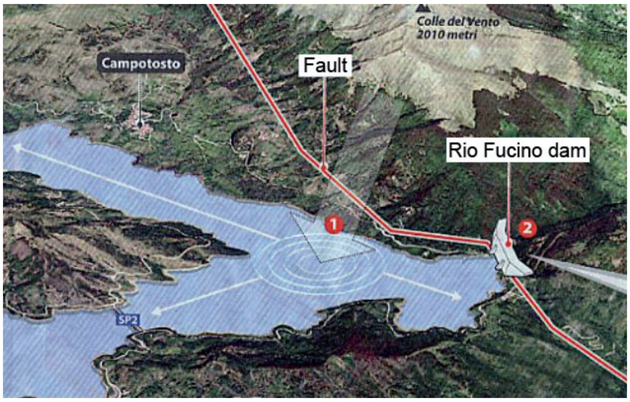

Fig. 13 - Campotosto Lake with one of the seismogenic faults crossing it (Geological Sheet 139 - Amatrice (1954), resumed by INGV and La Republica (August 2017). It is conceivable that the fault across the lake has played a very important role in draining water into the depths, thus operating producing the first preferential course way to the "lubricating" actions along its's own surface

that territory area to the water of Lake of Campotosto, which, over the decades, penetrated a few kilometers in depth along the fault itself, "lubricating" the milonitic-cataclastic contact areas between the structures of the area, triggering the seismic crisis with the aforesaid mechanisms.

CONCLUSIONS

Given what previously reported, it can be said that, in general, dams and artificial lakes do not cause earthquakes. Nonetheless stress and pressure on mechanical discontinuities (fractures, faults, etc.) due to natural (tectonic) causes accumulated in the crustal rocks maybe even in the sites where dams are built and they can reach the critical resistance thresholds that generate new faults or slide of the preexisting ones. In these areas strains and increments of "pore pressure" ("lubrication" effect), in fact, caused by the presence of artificial lakes can favor remobilizations along such discontinuities and even trigger or induce earthquakes, thus becoming the classic "*straw that broke the camel's*". The presence of a force source near the Earth's surface (such as the pressure exerted by the water of artificial lakes) can, in fact, generate artificial earthquakes alone or enhance the natural action which is the main cause, and it can be involved in liberating the potential energy accumulated in the Earth's crust by the tectonic processes.

Injecting a fluid in a fault zone reduces the frictional resistance, thus reducing the accumulation of elastic energy that normally occurs along the fault. In practice, the injection of a fluid serves to "lubricate" the fault, as said, while the extraction of a fluid serves to block it in its movements.

Therefore, if a certain amount of elastic energy is accumulating along the fault, when a fluid is injected along it, an earthquake knock occurs. Recent experiments showed that, by injecting or extracting fluids in deep wells, it is possible to turn on or off the seismic activity (seismic switch). It can be said that in both processes the common cause of earthquakes is due to the alteration of water pressure conditions in the underlying rocks (or around the permeability area). The result is reduction in pre-existing fractures, which facilitates the sliding of rock blocks along the faults or favors already existing breaks, thus triggering earthquakes.

Finally, with reference to the two reviewed Italian cases, although it is possible to estimate the loss of water by evaporation in an artificial basin, it is certainly very difficult to calculate underground losses to properly study the induced seismic phenomena; no reservoir operator, in fact, will be willing to report how much water the reservoir is losing, if possible, especially if it is located in seismic areas.

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