How nature reacts on human intervention

Responsibilities of those who cause and who interpret such reactions

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Summary. — The a. examines some of the replies given by nature to human intervention if subjected to disorderly stress. Cases of seismic shocks are reported, caused by extractions of enormous amounts of minerals, both fluid and solid, from the underground, or by the creation of artificial basins.

The extraction of large amounts of fluids from the underground is apt to bring about — and it really has — considerable ground flexures, as in the case of the Po River Delta, of the San Joaquin Valley, of San Diego and others.

Particular attention is given to seismicity caused by artificial basins which developed after the erection of large barrage dams. The author has been looking into these problems since about twenty years. Here he resumes some of the results of his experiences. Seismicity can develop in any watershed, without regard to its sizes and depth. It is in close relation to the preexisting field of elasticity: the more this is unstable, the easier microseismicity can develop. The lack of homogeneous physical rock conditions, even of geologically uniform basins, may become the cause of a local microseismicity, as is shown in the case of the Pieve di Cadore basin.

A "sleeping" tectonic disturbance can be reawakened with sometimes disastrous consequences (Vajont). The depth of the watershed is no determining factor for the building up of local seismicity. The artificial basin of La Maina (Sauris) has a depth of 130 metres, and yet local microseismicity is almost unexisting. The explanation is given by the extremely high rigidity of local rock which warrants of maximum of stability of the associated elastic field.

Microseismicity is not always connected with the pressure and the seepage of the water accumulating in the basin. Sometimes, the decompression following a rapid emptying may as well bring forth seismic shocks (Pieve di Cadore). It is repeated, however, that the formation of an artificial watershed is not always the cause of seismicity. There are examples in Italy,

besides that of the above said La Maina Basin, of wide watersheds created in seismic areas where microseismicity is least or does not exist at all (Mis, Ambiesta and others).

It is the author's opinion, anyway, that an artificial basin can never give rise to heavy earthquakes ($M > 4$). If they do happen with nearby epicentres, these are most likely cases of mere coincidence or of simple joint causes anticipating a phenomenon which would have occurred in any case. On the other hand, the chief concern in the preservation of dams and their respective basins is not so much represented by the action of strong isolated earthquakes as by the much more serious threat hidden in microseismicity, which over long time periods may disrupt inadvertendtly the molecular texture of the rock forming the support of the dam and of its entire basin.

In this regard the responsability of the men of science may not be overlooked, as they are called to discuss and to clear the causes of anomalies generated in the underground by more or less heavy interventions. Quite frequently the investigations of this kind are financed by the agencies in charge of the said interventions. And here the author leaves the specific cases behind himself for the sake of more general considerations. From the viewpoint of freedom and independence of judgment it is always dangerous to work on commission. Who engages in a research work, no matter whether he represents public or private interests, acts almost ever for particular purposes of exploitation, never in the interest of the common weal understood in its wider sense. It so happens sometimes, almost inadvertently, that the scientist gives away his dignity and works at the service of sometimes unconfessable interests. The poet singing the eulogy of the powerful has at all times been a character of cartoons, but the scientist acting on behalf of the powerful becomes downright grotesque. Human intelligence should never be the slave of the greeds of privileged classes or peoples, serving purposes of predominance or of exploitation, all the more as so nature is taking revenge for these outrages: the veils uplifted with malice often unchain forces which hit back against the conspirators or, much worse, against the innocent and the unmindful. It is right to work strenuously on the exploitation of nature's resources, but she must be faced in a mood free of ambitions and of greed, with the most humble and honest of intentions, with deep respect and due circumspection. Only in that way she gives generous replies and allows herself to be harnessed.

Scope. — The title may appear and really is, rather pretentious. I would point out, however, that it is not my intention, and that I would not be up to the task, to look into nature's reactions after having been subjected to human intervention. I shall limit myself to refer to the cases which I was fortunate, and infortunate enough, to submit to my personal examination, as well as to some others which I could observe here and there.

I am dividing the consequences of man's sizeable interferences with nature into two large groups: those of the *elastic* field and those of the *plastic* field. Attached to the first is *microseismicity* and *induced seismicity*, to the second the *deflections of the ground*, such as settlements, often referred to with the barbarism of " subsidence ".

1. – Microseismicity and induced seismicity.

1.1. *Microseismicity in the neighbourhood of large dams.* I have repeatedly enlarged upon this argument during the past twenty years (1-22). Here I am reassuming the aspects of microseismicity as I could record it in the neighbourhood of large dams and refer to the above quoted papers as far as particulars and interpretations are concerned.

Microseismicity in the neighbourhood of large dams may be *natural*, that is already existing before the building operations, or *latent* and, hence, reactivated by the disturbances of the elastic field which are caused by the series of explosions accompanying the removal of rock systems on which the dam is to be erected, or *induced* as a consequence of rock removal, of the dam's movements depending on the variations of the water level of the watershed on the mountain side, on solar radiation, on seasonal and casual climatic variations and other factors, of the action of the water filled basin, considering both the changes of bottom pressure and the effects of water seepage in unstable areas of the watershed or around it.

I limit myself to a few examples among the numerous cases I could observe in over twenty years. Concerning the Pieve di Cadore Dam, the seismic station installed there clearly announced already at the outset of its activity, on January 1951, a certain microseismicity whose typical features were undoubtedly connected to the existence of the dam and of its movements. Fig. 1 represents one of the many periods during which the microseismic crisis was evident. This kind of microseismicity so closely connected to the movements of a dam tends to attenuate in the course of time. In the case of the Pieve di Cadore Dam it came practically to a halt after the first five years following its construction.

The other kind of induced microseismicity (and seismicity) depends on the watershed and its variations. Here, too, I am limiting myself to two evidences.

Still referring to the Pieve di Cadore Dam, the periods of rapidly alternating rises and decreases of the water level, or of long decreases followed by rises, showed clear signs of induced microseismicity and seismicity. Of particular significance was the seismic period between 1963 and 1964. After having reached a maximum water level in October 1963, the Pieve di Cadore Lake gradually decreased, and by the end of March 1964 it could be considered virtually empty (Fig. 10b). The entire area within the influence of the lake was then subjected to an action of decompression, with subsequent changes of the elastic balance which became evident through some series of microshocks. The first occurred between March 5 and 26 and gave 17 microshocks which were recorded by the seismic station placed in the control room at about 22 metres distance from the dam. No distinction between longitudinal and shear waves was possible, considering the nearness of their origin, among the waves reaching the immediate neighbourhood of the seismic station (19). Another series of major shocks, some of which were felt by the inhabitants of the lake side, took place between May 10 and 18, 1964. The five most important, whose magnitude was in the order of 1.5 ~ 2, had their epicentre at some kilometres distance from the dam (19). Two were within the watershed, the others were marginal (Fig. 11). Successively, until July incl., there were other sporadic seismic activities of less importance. A total of 65 microshocks was registered from May to August.

The above said seismic events took place over a relatively wide area, once here, once there, with almost statistic regularity but without preferences. This is the typical feature of the microseismicity induced in the Pieve di Cadore watershed.

Things were rather different, unfortunately, in the Vajont basin. After completion of the dam and in correspondence with the first water fillings, an area on the left shore, on the mountain side, could be detected which gave rise to systematical microshocks caused by settlements.

South of that area (see Fig. 14) and elastic response in the body of Mt. Toc could be recorded through contrary signs, as if indicating a residue of orogenesis. The microshocks followed each other with particular frequency in October 1960, in the very area where later on the final collapse took place. I attributed to this series of microshocks the decay of the elastic features of the rock system of the left shore. It was indicated by an enormous decrease of speed of the elastic waves between December 1959 and December 1960. For details of this research work I refer to the specific publications appeared on the subject ([20-21]).

Here I would only underline the peculiar nature of the seismic events on the Vajont Basin, namely the existence of a well outlined area with an outspoken predisposition to disturbances in the elastic field in connection with the increase of the water level of the artificial lake. Contrary to what happened in the Pieve di Cadore Basin, where seismicity appeared widespread and disorderly on a rather wide area, the microshocks in the Vajont Basin came almost exclusively from the same area on the left shore which was probably affected by an old defect that was aroused again by the first fillings of the artificial lake. The existence of an overlying crumbly stratification before the disaster is symptomatic. Fig. 14 summarizes the outer aspects of this activity leading up to mortal consequences.

Even after the disaster of October 9, 1963 the seismic station, which had been rebuilt at the side of the dam, on the left shore, revealed again the same mechanism. Sudden increases of the remnant lake opposite to Erto caused hundreds of light shocks coming from the usual area.

So it happened with the flood of September 2, 1965 and again with that, of November 4-6, 1966. The matter has been widely discussed in the specific publications ([20-23]). Here I am only showing again Fig. 17 which summarizes the seismic activity of the Vajont area from 1964 to 1967. Since it has been possible to prevent rises of the water level of the remnant lake of Erto thanks to a broad discharge towards the Cellina Valley, the phenomenon has not occurred again.

1.1.4. Which are the causes of microseismicity induced in the neighbourhood of some large dams and in their watersheds?

I think that the microseismicity observed very close to some large dams is due to the movements of the dam itself, besides to the disturbance of the elastic field as a consequence of rock removal.

Once the Pieve di Cadore Dam had been built, a more or less strong instability could be observed within the basin. This was caused by the tendency of the rock system to assume new positions of equilibrium. The dam is subject to movements as the water level of the basin varies and following the seasonal thermic variations, bending once toward the valley, once toward the mountain side. In correspondence to these deflections sudden breaks of equilibrium in the elastic field take place and are indicated by long series of seismic shocks (Fig. 1) (*).

Some triangulations, executed periodically in the dam area, may furnish the necessary information to determine the variations of the elastic features. In fact, the measures of horizontal movements of determined points, as furnished by triangulations, may be used to calculate the components of horizontal deformation for each triangle (provided uniform deformation in an entire triangle) and allow as well to value the size and the direction of the chief deformations, of dilatation, of rotation and distortion, that is all the information enabling to characterize the elastic deformation (3).

Of course, I do not lose my time with theoretical problems which have been reassumed in the specific papers (13-14). I'm limiting myself in observing that, with reference to an arbitrary system of coordinates x, y, if u and v indicate the components of the displacement of a trigonometrical point, when the base line to which the measured horizontal displacements are referred is assumed unchangeable, one obtains for the *dilatation* Δ, for the *rotation* φ, for the *distortion* S, for

(*) As far as the Pieve di Cadore Dam is concerned, it may be said with reference to the geological nature of the area that the section in which the dam was built has been cut out of the dolomite rocks of Upper Trias (main dolomia) which develop almost perpendicularly to the axis of the Piave River. As a whole, the rock series of the left side appears regular and continuous, except for a few areas showing a little fractured rock. On the left side there are two different morphological types. The upper, based on the Pian delle Ere of 625 m of altitude, corresponds to the bottom of the track left by the old glacier of the Piave, while the lower corresponds to the deep cut made by the Piave River. The step-like base of the Pian delle Ere presents the same kind of rock forming the right side. Here, too, fractures of the rock are to be observed which have been caused by tectonic movements (Taken from a report by the late Professor Giorgio Dal Diaz). Successive researches conducted on the elasticity of the rock have shown, on both the left and the right shore, a very low Young modulus corresponding to mean longitudinal wave speeds of 2.2 km/sec for the rock above altitudes of 625 metres. For the lower height values the elasticity modulus is much higher, longitudinal wave speeds being of 4 and more kms/sec, while the base of the Pian delle Ere presents an extremely high modulus corresponding to longitudinal wave speeds varying between 5 and 7 kms/sec (2, 4, 21). It is to this unevenness of the elastic properties of the medium that the changes in the elastic field are attributed which are transformed into a diffused microseismicity exactly under the effect of the uneven response of the medium to the various stresses.

the *principal axes of deformation* e_1 *and* e_2, for the *angle* δ, that the direction of e_1 forms with the axis of the x, the following expressions:

$$\Delta = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \; ; \quad 2\varphi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \; ; \quad 2S = \frac{\partial v}{dx} + \frac{\partial u}{\partial y} \; ;$$

$$e_{1,2} = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \pm \sqrt{\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2} \; ;$$

$$\delta_{1,2} = \operatorname{arctg} \left| \frac{\frac{\partial v}{\partial y} - \frac{\partial u}{\partial x} \pm \sqrt{\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2}}{\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}} \right| .$$

The maximum distorsion assumes the expression

$$S_{\max} = \sqrt{\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y} - \frac{\partial u}{\partial x}\right)^2} = \frac{1}{2}\,(e_1 - e_2) \; .$$

Between August 15, 1949 and June 24, 1952, eight triangulations were carried out in the Pieve di Cadore Basin by the Società Adriatica di Elettricità (SADE). I considered it very interesting to elaborate geophysically the observations made, and summarized into tables, by those triangulations. Fig. 5 reproduces the displacements of the trigonometrical chain as they were measured in the said eight triangulations.

Figure 6 gives, together with the measuring bases, also the positions of the centres of gravity of the examined triangles. The method followed for the elaboration and the results of the heavy work have been summarized in publications appeared in 1957 (13) and 1958 (14). The calculations of the elaboration are collected in 14 tables; the graphical reconstruction of the elements of elastic deformation is contained in 35 tables. Here I am limiting myself to report the *dilatation*, the *rotation*, the *distortion* and the *chief axes* of *deformation* as they resulted in correspondence with the 4th and the 5th triangulation. It has been pointed out as a general observation that each triangulation was generally characterized by one sign only (positive — full line — negative) for the *dilatation*. This means that the entire dam area and the watershed examined gave rise *at the same time* either to *expansion* of the medium (positive dilatation) or to *contraction*. The variations of intensity and direction of these phenomena brought about more or less strong *distortions*. The chief axes of the deformation ellipses (stretched out or contracted) express with their lengths and directions the size of elastic deformation and the azimuth after which it developed. For the other interpretative comments reference is made to the above said publications. The explanations of these few lines should be sufficient, however, to *justify* the microseismicity connected in any case to the dam and brought to evidence during the first five years of operation of the big Pieve di Cadore Dam. The changes which had occurred in the elastic field are responsible for the thousands of microshocks recorded by the station near the dam. The epicentres of some of the chief minor shocks recorded in the 1950-1951 period, with magnitudes between 0 and 1, are indicated by asterisks in the plan of Fig. 4. One of the sectors from which came a great many of microshocks in the said two-year period is marked by β. I must be strongly emphasized that the said sector, which gave birth to the maximum number of microshocks, coincides with that part of the basin which after the calculations of the geodesy section of SADE became subject to the maximum translation action.

As far as seismic and microseismic activities in the Pieve di Cadore basin at a few kilometres distance from the dam are concerned, they were always associated with decreases and rises of the water level, such as during the already mentioned period from March to July 1964. The more intense shocks (M - variation from 1 to 2) must be ascribed to this kind of induced seismicity. There seems to be little doubt that this must be attributed to alternating states of decompression and successive compression during the passage from an emptying to a subsequent refilling stage. In an area of latent seismicity, such as the Piave Valley between Pelos and Perarolo, any change, also the slightest, of the surface elastic field may lead to microfractures of the order of those observed.

The microseismicity induced on the left shore, at the mountain side of the Vajont Dam, must be mentioned separately. To this microseismicity is attributed the demolition of the elastic tissue of the rock system supporting that part of Mt. Toc which rushed with lightning speed into the lake in the evening of October 9, 1963. In my very first reports on the subject, written in 1960-61, I had attributed the mischievous phenomenon in development to a tectonic contrast between a portion of the left shore, which was subsiding, and the slopes of Mt. Toc which were perhaps still subject to residue forces of orogenesis. This hypothesis was underlined in further reports up to a few days before the disaster [20]. Later on [21] another hypothesis was heard of, after which the area that was about to sink down suffered a suction action by the North-South sliding tendency of the underlying stratification into which it reached partly down. This brought about an opposite effect on the collateral slopes of Mt. Toc. This hypothesis gave great importance to the action — yet existing as a mere tendency — of a fossile branch of convection current whose remnant movements were perhaps influenced by the overlying watershed. Drillings successively carried out in neighbouring areas lead to think that the hypothesis is not hazardous at all (24).

But this subject is not exhausted with the above considerations. Some research work has been done recently on cases having a certain analogy and has led to a new hypothesis on the mechanism bringing about certain earthquakes (25). Two years ago a new theory on the origin of earthquakes was expressed which attributes them to an extention failure (26). The theory describes a new mechanism which operates when a liquid is present in a fractured solid non homogeneously subjected to pressure. Of course, I cannot enlarge upon the new theory. The only observation I make is that due to its aspects it is applicable to the microseismicity of the limited area of Vajont which I have mentioned several times.

Water seepage, which is particularly abundant in periods of maximum fillings or of sudden rises of the watershed, lay the foundations of the above said mechanism. The clear division into a dilatation area and a compression area constitutes another factor in favour of this theory.

The shearing phenomena caused by hydraulic underground injections have been the subject of numerous publications of which I can mention only a few (27, 29). It is too well known, moreover, that these injections may cause regular earthquakes. Considerable evidence in this regard has been furnished by Evans and collaborators (30-33) concerning the long series of earthquakes caused in the Denver (Colorado) area following the waste water injections carried out by the U. S. Army in a nearby mountain area, the Rocky Mountain Arsenal northeast of Denver. Figure 18, proves the close connection between underground water injections and seismicity in the Denver area. In the neighbourhood of American dams, too, a local seismicity could develop which is attributed to the action of the watershed (Carder, Evans...).

Concerning the microseismicity observed on the left shore, at the mountain side of the Vajont Dam, there is considerable evidence that before and after the disaster it must be attributed to water seepage under a certain pressure (maximum fillings) in an area strongly inclined toward seismicity.

1.1.2. Of course, not all artificial basins are subject to induced microseismicity. The seismic stations operating with some dams of the Veneto Region record only with extreme rarity activities that may be attributed to disturbances coming from their watersheds. The large artificial basin created in the upper Lumiei Valley (Carnia) by a 136 metres high dam, has never (at least thus far) been the seat of induced microseismicity, although it has level differences of 40, 50 and more metres. A few rare microshocks come from an old landslide area on the left shore, below the village of Lateis. This proves a considerable stability of the local elastic field which is witnessed, by the way, by the very high speed of the longitudinal waves measured there, with values close to 7000 m/sec in some sections of the springer rock of the dam. Not even the Ambiesta Basin (a right shore affluent of the Tagliamento River, near Tolmezzo) has given rise to microseismic circles properly speaking, although this geologically very tormented area presents a high seismicity rate. The Mis Basin, too, near Sospirolo, showed only a rare seismic action which may be attributed to induced microseismicity.

In this respect I have to point out something. An initial period, in which the possibility of earthquakes caused by artificial watersheds met with general scepticism, was followed by another period, the present which is characterized, in my opinion, by an exaggerated attribution of all earthquakes in the neighbourhood of an artificial basin to the building of the latter. I do not believe, for instance, that any earthquake of a magnitude over 4 may be attributed to the presence of artificial basins in the epicentre area ([53]). If this does happen, it is my belief that the fact should be considered a mere coincidence or even a concomitant cause, there being no doubt that the earthquake would have occurred anyway for natural causes, which are much more efficient, and that in some way it has been anticipated by the disturbing action of the area's elastic field which had been caused by the artificial watershed.

In a recent study on seismicity in the area of the Mangla Dam (Pakistan) ([52]) earthquakes with epicentres at 20, 25, 30, 40 and more kilometres distance from the water reserve are attributed to the later's action. In full consideration of the largeness of this basin, which covers an area of 250 square kilometres with a mean depth of

26 metres, a correlation between the disturbing action associated with the basin and earthquakes at such distances should hardly be accepted.

1.2. – *Seismicity induced by disorderly extraction of minerals.*

Two considerable shocks were recorded in the Lodigiano area on May 15 and 16, 1951. Their epicentre was not far from Caviaga. The shocks were recorded in the epicentre area as VI-VII and V-VI, respectively, of the Mercalli scale. The surface distribution of the initial movements of the longitudinal waves led to an unusual configuration (Figures 20-21), inconsistent with those observed in previous studies on Alpine and Appennine earthquakes. The earthquake of May 15 proved to have been caused by a break of the elastic equilibrium which had occurred in a vast area, chiefly developed in the North-West quadrant, with the features of compression, exactly a thrust toward outside. The area itself appeared clearly decentralized against the epicentre, which led to presume that the disturbing cause had acted, with a sudden pressure, along an axis that was strongly inclined against the vertical and in SE-NW direction. The mechanism of the second shock, too, was strongly analogous to that of the first. Only the axis of the area subjected to compression had a slightly different inclination against North.

In the extensive work dedicated to the shocks in question [34] the hypothesis is expressed that the cause of the earthquakes of May 15 and 16, 1951 is not entirely natural, but includes human intervention, too. I am quoting a writing of the time:

" We observe that the epicentre falls precisely into the neighbourhood of Caviaga, a place where natural gas wells are existing from which considerable amounts of methan gas, ranging from 10.000 to 300.000 m^3 per day, are extracted. The depth of the methane layers in this area is about 1250 – 1450 metres below ground level, and maximum pressure at the mouths of the gassers varies between 130 and 140 kg/cm^2. There are, however, in the Lodigiano area other natural gas fields with similar extractions of methane and with pressures at the mouths of the gassers of the same order as above, if not higher. This extraction has been going on for years, and the area is subjected, therefore, to a considerable decompression. One may get an idea of these decompressions bearing in mind that the extraction of one million m^3 of gas per day, at a pressure of 100 kg/cm^2, would correspond to a daily work of 10^{20} erg. Such a decompression is, therefore, really high.

The discharge of energy is gradual, of course, not instantaneous, as is the case with earthquakes. It cannot be denied, however, that in the underground this enormous amount of compressed gas, too, has a balancing effect.

Its action varies with the geological structure of the area which may be such as to cancel virtually any disturbing effect, as it may also facilitate the trend toward new balances which not always are reached " gradually ".

Further arguments in favour of this hypothesis are given on pages 96 and 103 of the above paper. After a 15 year interval since its publication I still think that the hypothesis is fully valid. As may be gathered (see Figures 20,21), the superficial division of compressions and dilatations is well consistent with the effect of a violent thrust toward outside, after a solid angle having its axis strongly inclined toward NW. The peculiarity of the shock mechanism, the fact that in the notoriously aseismic area very sizeable extractions of natural gas were conducted, strongly suggest that the break of the elastic field, as it had occurred there, is in some way to be associated with the enormous decompression in the deeper layers from where the gas broke forth under pressures in the order of 150 kg/cm².

By the way, phenomena of this kind have taken place in other parts of the world. Limiting ourselves to Europe, I will only recall that Belgian geophysicists are attributing the increasing seismicity of Belgium's coal fields to the more intense extraction of the mineral.

In this regard it should be remembered that similar phenomena developed in the Raibl Mine, near Cave del Predil between 1965 and 1967. On November 13, 1965, after noon, a strong telluric shock brought panic to the population. In the Cave del Predil Mine, where lead and zinc ores are extracted, there were numerous thrusts in various tunnels. Fortunately no worker was in the mine at that time. The beginning of the earthquake was registered at the Tolmezzo seismic station at 12h 22min 43.9sec, and a similar recording was made at Somplago, in the ENEL electric Central built into the rock. As occurs in all the mines of the world, in the Predil mines there were the so-called rock explosions from time to time and at various levels, that is small blasts within the uncovered rock, due to decompression.

During the months prior to the earthquake, however, there was an unusual increase of the number of rock explosions which was particularly marked in August and September. It was clear that a considerable change of the elastic field was going on in the area, with increasing tensions, which led to the provisional outburst of the earthquake of November 13, 1965. I say "provisional", because that shock, unfortunately had not entirely rid the area of the tension that was building up.

Little more than a year afterwards the papers wrote again about the Cave del Predil. In the evening of March 6, 1967 a section of a tunnel in the mine broke down under an earthquake shock. Of the five workers present two were buried under the debris and one of them lost his life. As the press put it ("Il Tempo", March 7, 1967), "the telluric shock was felt by the entire population, houses quivered and various window panes were broken". And that this was a real earthquake, though less intense than the one of November 13, 1965, was evidenced by the recordings made at Tolmezzo and at Somplago, at over 50 kms distance.

2. – Subsidence of ground after disorderly extraction of minerals in the fluid state.

In 1956, when I was appointed a member of the Ministry Committee that was to look into the abnormal subsidence which had been observed for some years in the Polesine Region, my knowledge of this kind of phenomena was rather limited and uncomplete. After a few months' study of the local conditions and of proper confrontation with the enormous amount of methane waters extracted by thousands of wells operating all over the Polesine and in the Po delta, I became more and more convinced — and so did other members of the Committee — that the disorderly extraction of liquid from the underground had to be considered chiefly responsible for the flexure of the Polesine lands. Unfortunately, what was straightly evidenced to me and to a few others found the most strenuous opposition on the part of the organisation interested in the exploitation of the methane waters (Consorzio Italiano Metano – C.I.M.) which availed itself of worthy public officials and of some well known experts of geology, geodesy and geophysics in its action of denying any responsibility for the extraction of the waters. In order to counterattack the largely fraudulent argumentations with which it was tried to prove that the enormous pumpings of methane waters from the underground had nothing to do with the abnormal subsidence, I was obliged to do a capillary research work on the matter, consulting international literature and exchanging numerous letters with public offices and scientists who in other parts of the world studied the variations of the ground level as a consequence of whatever causes there had been. It was in that stage that my knowledge on this matter was widened and deepened. Among other things I became aware that, contrary to CIM's and its experts' stubborn assertions, anywhere in the world there had been and were developing abnormal subsidence processes, these have been systematically associated with enormous underground extractions of liquids and of gases. These witnesses were so overwhelming and numerous that my conviction on the cause of the Polesine subsidences changed into certainty.

Among the most outstanding ground settlements connected with abnormal extractions of liquids and of gases mention should be made of those of Azuma and Oshima (Japan) between 1940 and 1950, of Wilmington (Long Beach) with climaxes up to 8 metres (36,45), of those of the San Joaquin Valley in California covering a rather wide area (46-48). All these movements had been caused by extensive extractions of hydrocarbons (Long Beach) or of water. In a long report submitted to the Ministry of Public Works in May 1959 (published in 1967) (36) I concluded by suggesting the immediate shutting of the methane wells operating in the Po Delta if one intended to block at least partially a situation of continuous hazard.

The gradual closing of the wells operating East of Adria, beginning with 1960, proved how well founded these argumentations were which led to the Ministry's late decision.

3. – Responsibilities of party-named experts in estimating the consequences of protracted human intervention capable of changing the natural equilibrium.

During the last decades underground extraction of minerals or water have become more and more abundant and widespread. Construction of artificial basins, too, has taken a considerable development and the extensions and depths of artificial lakes have been growing continuously in proportion with the growing sizes of barrage dams.

The first attributions of variations in the elastic field, associated with heavy interventions of mining industries, had to meet with utter scepticism or indifference from both the parties interested in the mining operations and their experts. I remember, in this regard, the angry reactions of certain engineers when it was announced that the clinographs, for the first time installed in a dam, indicated daily variations of inclination associated with the effect of sunbeams; it was unconceivable to them that a dam could bend under such "modest" actions. The explanation of such attitudes is that the idea of a static, imperturbable nature, which stands firm against any outer intervention, has been and still is widely diffused. The attribution of the earthquakes of May 15 and 16, 1951, near Lodi, to the enormous gas extractions in the quadrilateral between Basiasco-Caviaga-Cornigliano-Ripalta was received with laughter in Italy. The reaction abroad was different. The explanation was reported as trustworthy by C. F. Richter on page 156 of his " Elementary Seismology " (35).

The continuous, stubborn and sometimes violent opposition to the attribution of surface layer flexures to heavy human intervention was conducted unanimously and with a maximum of initiative, between 1955 and 1960, by CIM officials and experts against the few who " dared " see and evident connection between the subsidence of the Delta and the extraction of methan waters. Practically all official Italian representatives of the world's sciences (geologists, geodesysts, geophysicists) agreed in denying such a correlation. It is not my intention to recall the heaps of writings of those years on the subject: articles in newspapers, magazines, scientific reviews, academic reports, press conferences etc. Only some of the most significant ones can be mentioned here (37-39).

In a publication of 1957, signed by a geodesyst, a geophysicist, an oceanographer and a geologist (40), all C.I.M. experts, after various peremptory confutations and illations on the complexity of the problem, no less than ten different series of investigations to be conducted in the Delta and the adjacent sea are listed, and the hope is expressed " that from the sum and from a selection of all geodetic, geophysical, geological, oceanographical data general conclusions for a valid interpretation of the phenomenon may be gathered " (page 15). Among the complex investigations suggested, which would have required decades to be implemented, the most obvious one was missing: the simultaneous cessation of methane water extraction in a determined area. A paper written by another geologist (41), after having discussed the phenomenon occurring in the Po Delta, proposes at last a series of eight complex investigations, upon which it should be possible to arrive at "a fruitful discussion and a conclusion on a reasonable basis". The author adds, however, immediately that " considering the enormous work required to look into the manifold aspects of the difficult question and to answer them after an ample consideration, one cannot but think melancholically of the poor Committe of brave men which had been summoned by the Ministry to submit within a few months' time their well pondered judgment ". Here, too, one omits to enlarge upon the " experimentum crucis " which could have discovered, really in a few months, the cause of the frightening subsidence that was going on. Still another geologist, on writing about the quaternary Polesano – Ferrarese Basin and its natural gas fields ([42]), mentions the abnormal subsidence of the Po Delta and reaches this conclusion: " At last, everything leads to believe that the exceptional settlements of the ground surface, that was witnessed in the region of the Po Delta, is generally in no relation with the extraction of methane and of the water accompanying the gas ".

I could go on with these judgments, but the few I have repeated here should be sufficient to prove how massive and compact the array of official science was against the attribution, even to a certain extent, of the flexure of the Delta, to the extraction of methane water. No wonder if the President of C.I.M., strengthened by such declarations, railed in the very sense of the word at all those who, in his opinion, " dared bring an action against methane ", with " illogical impeachments and unworthy requests " which had to be definitely repulsed (*).

But this was not enough. The more or less disputable opinions expressed to acquit the extraction of methane water were accompanied by sensational figures regarding ground settlements developing in other parts of the world where no underground extractions whatsoever were in course. It is sufficient to quote in this respect the assertions made by one of the C.I.M. geophysicists during a discussion on the above mentioned report by Prof. Dal Piaz on " The Quaternary Basin "

(*) It is worth mentioning that the " unworthy requests " concerned the suggestion of closing down, on the experimental level, a certain number of methane wells. To use the words of the President of the Consorzio Italiano Metano (C.I.M.), this suggestion had to be repulsed without the least hesitation, " because it calls for an experiment which is not only burdensome and very grave, but above all of an ambiguous, doubtful, if not downright impossible interpretation " (From one of the press conferences of the President of C.I.M., held in Milan on Jan. 8, 1958, as appeared in the " Gazzetta del Veneto " of Jan. 10, 1958).

published by the «Accademia dei Lincei». Here the words of the geophysicist: " ... according to information I have recently received, in various regions and in various periods there have been ground settlements in the order of 20 cms per year in an area of the Mississippi Delta where no methane extractions are in course: these data have been published and studied by the Corps of Engineers of the United States. In more recent times... Russell reports a value of 30 cms per year for ground settlements which are anything but exceptional in the area of the Mississippi Delta, in an area, I am repeating, where natural gas is out of discussion since there is no methane extraction " [43].

These data placed the President of the " Consorzio Italiano Metano " in a position of raging against the few opponents: in one of his numerous press conferences [44] the latter are defined as "superficial accusators of methane ", " who do not think nor know, because of their scarce information". As to the above figures he declared " It is desolating that the superficial accusators of methane, who have nowadays gained knowledge of the subject, though not through their proper science, feign to ignore them completely as they feel to be unable to refute them and continue to repeat with unshakeable candor and tirelessly their ideas ".

Which could be the state of mind of the " brave men ", referred to in the above mentioned report of the late Prof. Gortani, who constitute the " poor " Committee of the Ministry? In spite of everything, some of the " brave men " did not surrender. Concerning myself, I succeeded in proving after two years of hard work, as already mentioned, how fallacious were the assertions of the various experts and that the data on abnormal ground subsidence (*), which the said geophysicist claimed

(*) As I was able to show in my repeatedly mentioned paper, those data have not the least reference to reality. No trace is there of any 20 or 30 cms per year. Russell [19] had mentioned 2 inches per year in 1936, referring to the maximum subsidence observed in South-Eastern Louisiana, and exactly on a telegraph cable stretched over a place called " The Jump " and checked between the years 1853 and 1877. All other ground settlements recorded in the Mississippi Delta proved to be of a negligible entity. The data in question are taken from " Geology of the Mississippi River Deltaic Plain — Southeastern Louisiana " [50,51], published by the same " Corps of Engineers " which — according to the aforementioned geophysicist — was " engaged in very detailed research work, both on the dynamics and on the other possible causes of the movements ... going on in the Mississippi Delta ". It was exactly the said " Corps of Engineers " which, upon my request, to have observed in the Mississippi area and elsewhere, in spots without natural gas extractions, were altogether erroneous. In May 1959 I submitted to the Ministry the above said ample report (published in 1967) ([36]) at the close of which I called for the immediate shutting of the thousands of methane wells in operation in order to save at least a part of the Po Delta.

3.1. After these considerations and with particular reference to the subsidence of Po Delta, the question arises what damages have been done to the Region by the attitude of the official science which denied unanimously any responsibility of methane extraction for the flexure of the delta, and especially by the violent refusals of the President of C.I.M. who had been supplied apparently unshakeable arguments by his experts, for instance those resumed in the data of abnormal subsidence in the Mississippi Delta, in spots where no natural gas extraction was in course, and which had no real foundation at all, as we have seen. No doubt that the damages are enormous.

Fig. 22 gives a synthesis of the abnormal ground subsidence occurred in the Polesine area and in the Po River Delta from 1951 to 1958.

Figures 23, 24 resume the abnormal settlements occurred in the same area in the years 1958 and 1959 respectively.

Fig. 25 summarizes the abnormal settlements associated with the 1958-1963 period.

At last, in the year 1960, by overcoming a resistence which can be easily imagined, considering the opposition of the interested party which could depend on the judgments of so many " lights ", the Ministry Committee (better defined the "poor" Committee of the Ministry) succeeded in enforcing the close of wells in a limited area (see the polygonal in Fig. 26). In the area the settlement diminished as by magic and the water level in the wells rose again. In view of these results the Ministry ordered the wells of other areas to be closed between the years 1960 and 1964. The consequences of these shutdowns are resumed by the figures of the publication mentioned several times. In any case they may be roughly summarized by Fig. 27.

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denied any validity of the enormous subsidence data named in the above mentioned Congress which was organized in 1957 by the « Accademia Nazionale dei Lincei » and E.N.I.

The consequences of the delayed shutdown of the methane wells in the Po River Delta are in few words:

1) If the wells had been closed in 1957, as it had been proposed, the abnormal settlements observed in 1958 (varying between 20 and 30 cms in some points) would have been avoided, as would have been avoided the heavier ones of 1959 which in various zones led to subsidences of as much as 35 cms.

2) To be short, a shutdown of wells in 1957 would have avoided the settlements reported in Fig. 25 ranging from a minimum of 30 cms to a maximum of 120 cms. The total of the flexure was enormous and has seriously injured — it may be definitely — the equilibrium between the emerging earth and the water in vast areas of the Delta. As is known, several of them are under water now 12 months per year.

I have enlarged upon the situation which has been prevailing in the Delta after the disorderly extractions of methane water, first because I took part in the investigations which discovered the causes, and secondly in view of the consequences brought about by such settlements in only apparently far off areas, for instance in the Venetian lagoon, and finally to emphasize the responsibility of hasty judgments, often dictated by interest and expressed by many outstanding people, but contributing to the protraction and, hence, to the aggravation of the phenomenon.

It is understood, of course, that a behaviour of this kind is not possible only with Italians. Desperate fighting on similar problems have been witnesses in other countries, too. In the United States, for instance, it was only after harsh controversies that David M. Evans succeeded — and only in part — to convince the authorities of Denver that the earthquakes that had been striking the town and the neighbouring areas for some time had been originated by injections of waste water in a nearby spot. In a letter of August 14, 1968 in which he adduced new witnesses to the connection between water seepage and seismic activity, Evans wrote to me " ... although the political authorities are doing their best to dodge the responsibility ".

It is clear, anyhow, that an authority, political or not, is induced to dodge (as Evans says) its responsibilities as long as it finds experts who, through their judgments, bolster such elusions.

Considering the dramatic consequences which the judgments of experts of the involved party may have on the development of the phenomena under investigation, it is the duty of such experts to let themselves be guided by the most dispassionate objectivity.

It is easy to explain that an expert tends to express, even in perfectly good faith, a judgment in favour of the party requesting his services, but it cannot be justified that to this end he puts forth data far from reality or not thoroughly checked.

The man of science, if he really wants to be one, must be at all times and exclusively at the service of truth.

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