Distribution: limited

FR/TA/CONSULTANT

pakistan

Seismic Effects at Mangla Dam

May 1967 & November 1968

by R.D. Adams

Serial No.975/BMS.RD/SCE
Paris, January 1968

unesco

CONTENTS

Serial No. 975

1. INTRODUCTION

Mangla Dam has been built across the Jhelum River some 200 km (125 miles) north-north-west of Lahore, where it enters the plain of the Indus Basin from the high country of the northern regions of West Pakistan. The dam is of earth construction, with a maximum height of 135 metres (450 ft) and forms a lake of an area of approximately 250 km^2 (100 $miles^2$) with a maximum gross capacity of 7200 x 10^6 m^3 (5.88 M.A.F.). The dam was impounded in two stages between February and September 1967. Due to the foresight of the Pakistan Water and Power Development Authority (WAPDA) and their consultants for the Project, Binnie & Partners of London, one seismograph station has been operating in the area since late 1965, and two others since the time of impounding. These stations are operated with the collaboration of the Geophysical Institute, Quetta, a branch of the Pakistan Meteorological Department. Mangla has thus become one of the few large dams in the world for which an adequate seismic surveillance has been carried out.

This report arises from visits made to Mangla under Unesco consultant contracts in May-June 1967 and November-December 1968 to advise WAPDA on the operation of the seismograph network and the interpretation of the resulting records. An earlier report described some of the technical problems associated with the study of near earthquakes, whereas this report discusses the more general question of reservoir-induced seismicity and the effect of the Mangla reservoir on the occurrence of local earthquakes

2. SEISMIC EFFECTS OF LARGE RESERVOIRS

For many years, engineers have been aware of the possible effects of earthquakes on large dams, and have incorporated earthquake-resistant features into their design. It is only recently, however, that attention has been paid to the inverse problem, to the effect that the addition of the large extra weight of the reservoir on the earth's surface will have on the occurrence of local earthquakes. The two problems are, of course, closely interrelated, for any large earthquake occurring in the immediate vicinity of a dam would cause a high intensity of shaking to be experienced there, and the consequent possibility of damage both to the dam itself and to other structures.

In October 1967, at the Ninth Congress on Large Dams held in Instanbul, the French National Committee on Large Dams reported, "It will be useful in the future, if for every large dam a network of seismographs be installed to follow before, during and after the construction, the forces applied locally to the earth's crust". At this time, several cases were known of minor increases in seismicity being associated with the impounding of reservoirs, but the only well-documented case of a damaging earthquake following such an event was that at Kremasta in Greece in February 1966, where an earthquake of magnitude 6 did considerable damage as well as causing many injuries and one death. Among the papers presented at Istanbul conference was one entitled "Earth Tremors in Koyna Project Area" by P.M. Mane, which described how small earthquakes had been felt in the previously aseismic region around the Koyna Dam in Western India, from a few months after impounding in 1962 until the time of writing. He reported that:

"The tremors still continue without much variation in their frequency, intensity, or total energy released. A tendency towards gradual and successive reduction and decay was noticed in the first three years, but they have again increased to what they were in the first year, though there have been no significant changes in the physical conditions, viz, of height of the dam or the quantity of water stored ..... It is gathered that such tremors gradually decrease over a period of some years and stop completely. It is hoped it will be so here also."

Two months after this paper was presented, an earthquake of magnitude 6 1/4 occurred within 5 km of the Koyna Dam, resulting in more than 200 deaths and causing much damage. It has been suggested that this earthquake was not connected with the filling of the reservoir, but the seismological evidence for such a connexion is very strong. The area is one which had experienced no earthquake of significant magnitude since the beginning of instrumental recording, and where on geological and geophysical grounds there was no particular reason for a large earthquake to be expected. A paper "Koyna Earthquake" by Narain and Gupta (1968) clearly attributes the earthquake to the effect of the reservoir and a similar view is taken by Prof. J.P. Rothe, Secretary General of the International Association of Seismology, in a recent article "Fill a Lake, Start an Earthquake" (1968).

An increase in local seimicity does not always accompany the filling of a reservoir. No such effect, for example has been observed in New Zealand, where the largest artificial reservoir, Lake Benmore, has a capacity of 2.3 M.A.F., comparable with that of Koyna. Also, where seismicity has been observed, its pattern has varied in different cases.

The first well-documented study of reservoir-induced earthquakes was that by Carder (1944) following the filling of Lake Mead in the United States. Filling started in 1935, and no earthquakes had been reported from the area in the 15 years before the first felt shocks in September 1936, which coincided with the peak water level of that year. As the lake rose during the next 15 months, the felt shocks continued. The peak of recorded earthquakes was in May 1939, about 10 months after the lake had reached its full height for the first time. In the years 1940, 1941, and 1942 the peak in seismicity followed maximum reservoir load by a delay of several weeks, whereas in 1939, 1943 and 1944 it occurred at times of maximum river floods when the lake was rapidly rising. The earthquakes occurred mostly within 20 km of the centre of the lake, and the largest shock had a magnitude of about 5.

A rather similar pattern of seismicity was reported by Galanopoulos (1967) for the earthquakes which followed the filling of Lake Kremasta in Greece. It was the largest of these earthquakes, on 5 February 1966, which has been mainly responsible for the recent revival of interest in the earthquake-generating potential of large reservoirs. This earthquake, of magnitude 6 1/4, resulted in one death and injuries to 60 people, and caused serious damage or collapse in about 1700 houses. It occurred as the level of water in Lake Kremasta was approaching full height for the first tiem, with a rate of filling which had increased sharply since the previous November. About 100 earthquakes were recorded close to the lake in the month before the main earthquake, with the frequency of occurrence increasing as the time of the main shock approached. For 15 years before the Kremasta earthquakes, no shock had originated within 40 km of the dam. From his studies of the Kremasta earthquakes, and of small earthquakes near Lake Marathon in Greece, Galanopoulos concluded that such earthquake occurrence is proportional to rate of change of reservoir level.

Other cases of reservoir-generated earthquakes have been reported. Lombardi (1967) mentions small shocks accompanying the "exceptionally rapid rise of water during the first filling" of the Contra Dam in Switzerland, but reports that they stopped as soon as the level was dropped and heve not accompanied rises in level during the subsequent seasons. Rothe (1968), in a review of this subject, also mentions the earthquakes at the dam at Monteynard in the French Alps, which started a few days after filling commenced, and included a shock of magnitude 5.

As a final example of the basic pattern of earthquakes accompanying the initial filling of a reservoir, may be cited Lake Kariba on the border of Rhodesia and Tanzania, still the largest artificial load to be placed on the earth's surface. The detailed study of these earthquakes by D.I. and W.I. Gough has still to be published, but earthquakes of up to magnitude 6 occurred in this previously aseismic region as the lake was filled.

Other trigger forces besides loading by artificial lakes have been known to affect the occurrence of earthquakes. Berg (1966) has reported a connexion between the state of the sea tide and the occurrence of aftershocks of the Alaskan earthquake of 1964, while Guha, Ram and Rao (1956) suggest a relationship between river flooding in the Ganges Basin and local seismicity. More recently, the disposal of chemical waste fluids down a deep borehole near Denver, Colorado, appeared to be closely connected with an outbreak of local earthquakes (Evans, 1966), although subsequent more detailed studies by the Colorado School of Mines have revealed that the relationship of the waste disposal to the mechanism of the earthquakes is not as clear as was at first thought.

It is probably the delayed effect of the filling of the Koyna Dam that is the most puzzling piece of evidence yet obtained, and this earthquake has stimulated further interest in the triggering of earthquakes. All major reservoirs should now be subjected to seismic surveillance during impounding, for such surveillance is not only essential for monitoring any increase in seismic activity that may precede a damaging shock, but may also give valuable information regarding the fundamental causes of earthquakes themselves, and help towards their eventual prediction. Such an advance would enable the damage and suffering occasioned by them to be greatly reduced.

3. THE MANGLA SEISMOGRAPH NETWORK

A seismological observatory was set up in New Mirpur Town in August 1965, in collaboration with the seismological service of the Pakistan Meteorological Department. Mr. Asghar Ahmed was seconded from the Geophysical Institute, Quetta, as Officer-in-Charge and Mr. Abdul Razzaq as his assistant. Two further stations were set up in 1967 with equipment provided by WAPDA.

Details of the stations are as follows:

MIRPUR 33° 08' 50" N, 73° 45' 00" E, elevation 436 metres.

	Instruments	Components	Magnification
August 1965 to March 1967	Willmore MkII	Z,N,E	5,000
	Willmore MkII	N	1,700
Since March 1967	Willmore MkII	Z,E	5,000
Since May 1967	Wenner	Z,N,E	Strong motion

BARAL 33° 07' 04" N, 73° 36' 58" E, elevation 313 metres

	Instruments	Component	Magnification
Since March 1967	Willmore MkII	Z,N	1,700

JARI 33° 05' 50" N, 73° 50' 48" E, elevation 330 metres.

	Instruments	Component	Magnification
Since May 1967	Willmore MkII	Z,N	17,000

The position of these stations relative to the reservoir may be seen in Fig.1.

All stations are equipped with Willmore portable recorders, and since 1967 have operated from trickle-charged batteries so as to be unaffected by interruptions in the mains power supply. Minute marks are obtained from Sprengnether TS100 crystal clocks. Radio time signals were impressed on the records manually until November 1968, when 1,000 c/s filters supplied by the Seismological Observatory, Wellington, were installed, enabling the time signals to be recorded directly.

The Willmore seismometers used are ideal for this type of work, but the Willmore portable recorder is not the most suitable now available for observatory work. Its small size and its advantage of being operable from batteries in a space that need not be light-proof make it ideal for temporary work in the field, such as studies of aftershock sequences, but for a semi-permanent station a conventional observatory recorder is more reliable, and produces a larger record which is easier to interpret. Such a recorder needs, however, to be operated in a light-proof room, equipped with a light-trap for entry. At all three stations of the Mangla network, the seismographs are placed on extensive concrete piers, extending about 7 ft below floor level. Such foundations are not necessary for modern short-period instruments of the Willmore type, for which a small concrete chamber let into the ground is adequate so long as it is well bonded to the underlying rock.

The location of the three seismograph stations was determined largely by logistic reasons and the availability of existing buildings and roads. From the seismological point of view, the stations are rather close and too nearly collinear to be fully effective in locating earthquakes. For the proper location of earthquakes throughout the area, a fourth station to the north of the reservoir would have been desirable, but the establishment of such a station was not considered initially because of difficulty of access. The necessary equipment to establish a fourth station is now available at Mangla, and should the seismicity of the area show a marked increase, this should be set up to the north of the reservoir. It appears that a site in the Chak Swari area would be suitable.

4. EARTHQUAKES IN THE MANGLA REGION

Natural earthquakes occur in a broad belt extending along the high country of the northern boundaries of West Pakistan, with areas of lesser activity extending to the south. The largest shock to have occurred in the region was that near Kangra in 1905, which had a magnitude of 8.6, making it a major earthquake by world-~~s~~tandards. This earthquake originated only 220 km (135 miles) from Mangla. In 1885 an earthquake of magnitude 7 occurred in Kashmir, about 130 km (80 miles) from Mangla and smaller earthquakes have occurred as close as about 30 km (20 miles). Although no detailed study of the seismicity of the area had been made before the installation of the Mangla seismograph network, it was appreciated that the area was one in which large-magnitude earthquakes, capable of producing high intensities, could periodically occur, and that the region to the north-east was that in which the earthquakes were most likely to originate.

The seismograph station at Mirpur was installed in August 1965, but, because of nearby construction work, the records of the early months were not as reliable as those obtained later. The earthquakes considered in this report will therefore be restricted to those recorded between January 1966 and November 1968. Only earthquakes occurring within a distance of one degree (111 km or 69 miles) of one of the seismograph stations will be considered; those occurring between latitude 32 3/4° and 34°N, and between longitudes 73° and 74 1/2°E are plotted in Fig. 1. This distance restriction was chosen because the seismic-generating effect of the weight of water in the reservoir would not be expected to extend to a distance of more than a few times the linear dimension of the reservoir itself, and also because at greater distances the higher incidence of natural earthquakes in areas such as Kashmir and the Hindu Kush would mask any changes in local seismicity due to the reservoir.

Details of recorded earthquakes are given in Table 1, which lists the date and time of occurrence of each earthquake, its magnitude and its distance from the seismograph stations where it was observed.

In locating earthquakes, knowledge must be assumed of the local seismic velocities and their variation with depth. In most continental areas of the world, the near-surface velocity for P waves is close to 5.5 km/sec., and that for S waves 3.3 km/sec. These velocities correspond to the seismic phases Pg and Sg, and have been assumed in this work for earthquakes closer than about 30 km (20 miles), beyond which it has been assumed that the first recorded phases are of the type P* and S*, which travel through deeper layers, at velocities of about 6.3 and 3.7 km/sec. respectively.

From one station, if both P and S phases can be identified, a distance to the earthquake may be obtained, but generally no information concerning the direction of the shock. The distances quoted in Table 1 are either derived in this way from the S-P interval at that station, or from the arrival time of a single phase, after the origin time has been fixed from another station at which both P and S have been recorded.

When an earthquake has been recorded at two or three stations, an attempt has been made to locate it. For an earthquake to be located with reasonable precision by a network of stations, it should occur within the network or at a distance from it compatible with its size. Because the extent of the Mangla network is only about 25 km (15 miles) earthquakes at greater distances than this cannot be located reliably; since most of the earthquakes for which locations are given are at thisdistance or more, their stated positions should be regarded as approximate only. This applies particularly to those positions dependent on readings at two stations only, for each of which there exists an alternative position on the opposite side of the line joining the two stations concerned. When there is this ambiguity, the position given has generally been chosen to occur in a region of known seismicity, and often also to remove it from a more populated area where it would probably have been felt. The epicentres quoted are usually rounded off to the nearest tenth of a degree (sometimes to the nearest twentieth), and patterns of linearity or grouping arising from these approximations should not be regarded as real. A few shocks, recorded at all three stations, have been located by the electronic computer programme of the Seismological Observatory, Wellington. These epicentres are given to the nearest one hundredth of a degree, although they are still subject to the same uncertainties arising from their distance from the recording stations as are the solutions derived by graphical means.

For the depth of an earthquake to be established reliably, it should be recorded at a station within a distance comparable with the focal depth. The earthquakes for which solutions are given here, are in general too far away from the nearest station to enable any accurate determination of focal depth to be made. There is no evidence to indicate that any of them were deeper than the bottom of the crust (about 33 km or 21 miles), and as the distances quoted for the nearest earthquakes may be taken as slant distances, these earthquakes cannot be deeper than a few kilometres. For the computer-determined epicentres, a depth of 12 km was assumed.

Magnitudes have been assigned from amplitudes measured on the horizontal components of the seismographs. These were corrected to a standard magnification of 2800, and then combined with a distance factor as given by Richter (1958, p.342), to derive magnitudes on Richter's local magnitude scale, M_L.

The events listed include all those recorded, and some of the nearer, smaller events may be due to slips on the edge of the reservoir. An event in March 1967 has been definitely associated with such a slip. This list may differ slightly from those published previously by the Mirpur Observatory, these differences arising from changes in interpretation, often as more information became available from other stations. On other occasions, there is genuine doubt as to whether a given event on the record has a seismic origin or is artificial. Thus, a few of the events listed may be spurious, and similarly some genuine seismic events may have been discarded. Every attempt has been made, however, to be consistent in interpretation.

Various features of the earthquake occurrence are displayed in Fig. 2, in which is also shown the variation of reservoir level and capacity. The earthquakes are first represented by vertical lines at the appropriate dates, with heights proportional to their magnitude. Next, a simple histogram shows the total number of earthquakes recorded in each calendar month. An overall increase in recorded events is evident after impounding, for in the 14 months prior to impounding a total of 23 earthquakes was recorded, an average of 1.6 a month, whereas in the 21 months after impounding there was a total of 86 earthquakes, or an average of 4.1 a month, representing an increase by a factor of about 2-1/2. Some of this apparent increase may be due, however, to the operation of the additional stations after impounding. It is also worth noting the lack of recorded earthquakes between 1 April and 12 July 1968 when the reservoir was at its seasonal low, which was followed by a comparatively large number of events in July and August, when the lake was rising rapidly to its seasonal peak. Many of these latter events, however, were small and were recorded at Jari only. The rapid decrease in lake level from September 1968 does not appear to be associated with any earthquake activity.

The total energy released by the earthquakes also shows a slight increase in the period after impounding compared with that before. Using the formula $\log E = 9.9 + 1.9 M_L - 0.024 M_L^2$ to establish the energy of each earthquake, the average monthly release of energy before impounding was 3.0×10^{15} ergs, compared with 5.6×10^{15} ergs after impounding. These energy figures are largely determined by the few earthquakes of greatest magnitude, and the increase is probably not significant.

Finally in Fig. 2 each earthquake is represented by a dot showing its distance from the nearest seismograph station at which it was recorded. This diagram again shows the concentration of close events in April 1967, following the initial impounding and again during the seasonal rise in July and August 1968.

Fig. 1 also shows the approximate locations of the earthquakes given in Table 1, and the position of the known faults in the region. The fault passing in a NW-SE direction near Kotli is part of the Main Boundary Fault, which marks the contact of the rocks of the Siwalik series (upper Tertiary sandstones and clays) with older rocks of the Murree series. The Murree series predominates to the north-east of this fault, and to the north-west of Rawalpindi, but the remainder of the area shown in Fig. 1 is covered by the Siwalik formations, which are estimated to be about 10,000 ft thick in the region of the Mangla reservoir. The faults shown in this series to the south and west of the reservoir are naturally younger than the late Tertiary rocks in which they occur, and there is no evidence as to the depth to which they extend beneath the surface. In this part of the Indo-Pakistan sub-continent, the main concentration of natural earthquakes is to the north of the Boundary Fault, but earthquakes of magnitude 6 have occurred as far as 220 km (140 miles) to the south of it, near Delhi, and smaller earthquakes have occurred near Lahore at a similar distance from this fault.

The earthquakes shown in Fig. 1 fall mainly in the north-east quadrant from Mangla, towards the Boundary Fault, but are in no way aligned with it. Another group of seven earthquakes lies in the north-west quadrant from Mangla, near the Kanshi River and to the north of it. Two earthquakes are located near Baral. There is thus no close relationship apparent between the known fault traces and the located earthquakes. Again it should be stressed that the position of none of these earthquakes is likely to be accurate to better than a few miles, and with the more distant shocks the error is likely to be even greater. The earthquakes closest to the reservoir were in general not large enough to be recorded at more than one station, and therefore cannot be located or represented on this map. Two earthquakes for which positions are given in Table 1 fall outside the area covered in Fig. 1. One (7 Aug. 1968) was too far north, and the other (30 July 1968) occurred to the south-east of Mangla in the Gujrat district.

5. CONCLUSIONS

The seismic effect of the impounding of Mangla reservoir has been slight. Since impounding, the number of recorded earthquakes within 70 miles of Mangla has increased from a monthly average of 1.6 to one of 4.1, and the average monthly release of earthquake energy has increased from 3.0×10^{15} ergs to 5.6×10^{15} ergs. It is open to question whether either of these increases is significant. Earthquakes that have been located by the seismic network occur mainly to the north-east of the reservoir, towards Kashmir, in an area of known natural seismicity. Another group of earthquakes has occurred in the valley of the Kanshi River, and two have been located close to Baral Colony. No earthquake large enough to be located precisely has occurred in the immediate reservoir area, but many small earthquakes were recorded at the Jari seismograph station only, as having occurred within ten miles of the station. The earthquakes recorded have mainly been of magnitude 1 and 2, not large enough to be felt, but some have reached magnitudes greater than 3. It may be significant that the most active periods of seismicity appear to be from the start of impounding in March 1967 until December 1967, and during the rapid rise in reservoir level from July 1968.

The seismic effect of the reservoir at Mangla has so far been less than that at many smaller reservoirs. Its total capacity is 5.88 M.A.F., compared with 2.3 M.A.F. at Koyna and 3.9 M.A.F. at Kremasta, where destructive earthquakes have occurred. It may be significant, however, that Koyna and Kremasta have larger mean depths (100 and 190 ft respectively) than Mangla (85 ft), since the average increase in pressure on the reservoir floor is proportional to the mean depth of water.

A further factor on which the seismic-generating effect of a reservoir may depend is the degree of local seismicity already present in the area. Two of the three dams where magnitude 6 earthquakes have occurred, Kariba and Koyna, are in areas that were previously of very low seismicity; the third, Kremasta, appears to be in an area of seismicity that is low compared with its surroundings. On the other hand, the filling of Lake Benmore in New Zealand, near a region of active seismicity, was unaccompanied by any seismic manifestation, although it is of comparable size and mean depth to Koyna. This pattern might be taken to indicate that where natural earthquakes are occurring to a significant extent, the addition of small trigger forces has little effect, whereas the superposition of additional stress in a quiescent region may be sufficient to initiate earthquake activity.

The type of near-surface rock immediately beneath a reservoir may also be expected to have a bearing on the occurrence of very shallow earthquakes such as might be induced by reservoir loading. At Koyna, the underlying rock consists of the horizontal basalt flows of the Deccan Traps, separated by layers of tuff and breccia, while at Kariba the lake is formed in a down-faulted rift valley in old rock, believed to have been in existence since the late Precambrian. The rock at both these places is thus much older and stronger than that at Mangla, where the lack of any pronounced seismic effect may be due in some degree to the weakness of the rock, allowing it to adjust gradually to the added load, rather than resisting and then failing suddenly.

In all discussion of seismicity near Mangla, it must be borne in mind that the area as a whole is subject to earthquakes of large magnitude, and that irrespective of any effect of the reservoir, high-intensity earthquakes will be experienced at Mangla periodically.

6. RECOMMENDATIONS

Although the seismic effect at Mangla does not appear to be large, experience at Koyna has shown that large earthquakes can follow impounding by as much as several years. During 1968 the reservoir level at Mangla did not vary greatly, the lowest level reached being 1122 ft. It would be unwise to reduce the seismic surveillance until after at least one seasonal cycle in which the reservoir is lowered to near its minimum level of 1040 ft, which corresponds to a capacity of only 0.6 M.A.F., barely 10% of its full value.

Although only a single station is needed to monitor the occurrence of earthquakes, the additional information derived by comparing records from a number of stations is essential for a full study of them.

My specific recommendations are as follows:

1. It is highly desirable that at least one seismic station should continue to operate in the Mangla area at least until the end of 1969, and preferably until the expiry of the agreement with the Pakistan Meteorological Department in mid-1970.

2. Since the additional expense of running the existing extra stations at Baral and Jari is very low compared with their capital cost and the cost of their installation, and since the scientific value from observations from three stations is far greater than that from only one, the stations at Baral and Jari should continue in operation together with the main observatory at Mirpur.

3. Although the installation of a fourth station would improve the precision of location of earthquakes in the vicinity of the reservoir, the present level of seismic activity does not warrant its installation. Should local seismic activity increase to a degree such that several earthquakes originating in the reservoir area are felt each month, a fourth station should be installed on the north side of the reservoir. For this station, a single component vertical seismograph would suffice, requiring visiting once every two days.

4. Experience at other dams has shown that large-magnitude earthquakes induced by changes in reservoir loading are often preceded by an increase in the number of small shocks, but this is not invariably so. Nevertheless, any sudden increase in the frequency and magnitude of recorded earthquakes, particularly within 50 miles of the reservoir, should be regarded seriously; should this occur during a period of rapid change in reservoir level, such changes should be reduced to a minimum, and then a gradual lowering of the reservoir commenced.

7. ACKNOWLEDGEMENTS

This work was initiated jointly by WAPDA and Binnie & Partners, with the collaboration of the Geophysical Institute, Quetta. To these organizations is due every credit for carrying out this programme. I wish to pay tribute to the work of the seismologists at Mirpur Observatory, Mr. Asghar and Mr. Razzag, who have maintained the seismograph network and undertaken much arduous analysis. My thanks are also due to senior members of the staff of WAPDA and Binnie & Partners, particularly Mr. M.I. Chishti, Resident Engineer Reservoir of WAPDA, and the Chief Resident Engineers of Binnie & Partners, Mr. J.R. Gwyther and Mr. B.G. Cox. I am also grateful for the interest shown in this project by Mr. A.L. Little of Binnie & Partners, London.

Finally, I wish to express my thanks to Unesco, under whose auspices this work was carried out, and to the New Zealand Department of Scientific and Industrial Research for allowing me leave from my post as Superintendent of the New Zealand Seismological Observatory to undertake this assignment.

8. REFERENCES

Berg, E. (1966). Triggering of the Alaskan earthquake of 28 March 1964, and Major aftershocks by low ocean tide loads. *Nature, 210,* 893-6.

Carder, D.S. (1944). Seismic investigations in the Boulder Dam area, 1940-1944, and the Influence of reservoir loading on local earthquake activity. *Bull. Seis. Soc. Amer., 34,* 175-97

Evans, D.M. (1966). Man-made earthquakes in Denver. *Geotimes,* 11-8, May-June 1966.

Galanopoulos, A.G. (1967). The influence of the fluctuation of marathon lake elevation on local earthquake activity in the Attica Basin area. *Ann. Geolog. Pays Helléniques,* 18, 281-306

Guha, S.K. Ram, G., Rao, G.V. (1956). Trigger causes in earth movements. *Publ. Bur. Cent. Intern. Seism., Trav. Sci.* Ser. A. Fasc. *19*, 345-55

Lombardi, J. (1967). Quelques Problèmes de mécanique des roches étudiés lors de la construction du barrage de Contra (Verzasca). *9th*. *Congress on Large Dams,* Paper R.15, 235-52.

Mane, P.M. (1967). Earth tremors in Koyna project area. *9th Int. Congress on Large Dams,* Paper C. 13, 509-17.

Narain, H., Gupta, H. (1958). Koyna earthquake. *Nature, 217,* 1138-9

Richter, C.F. (1958). "Elementary Seismology". Freeman and Co., San Francisco.

Rothé, J.P. (1968). Fill a lake, start an earthquake. *New Scientist,* 39, 75-8.

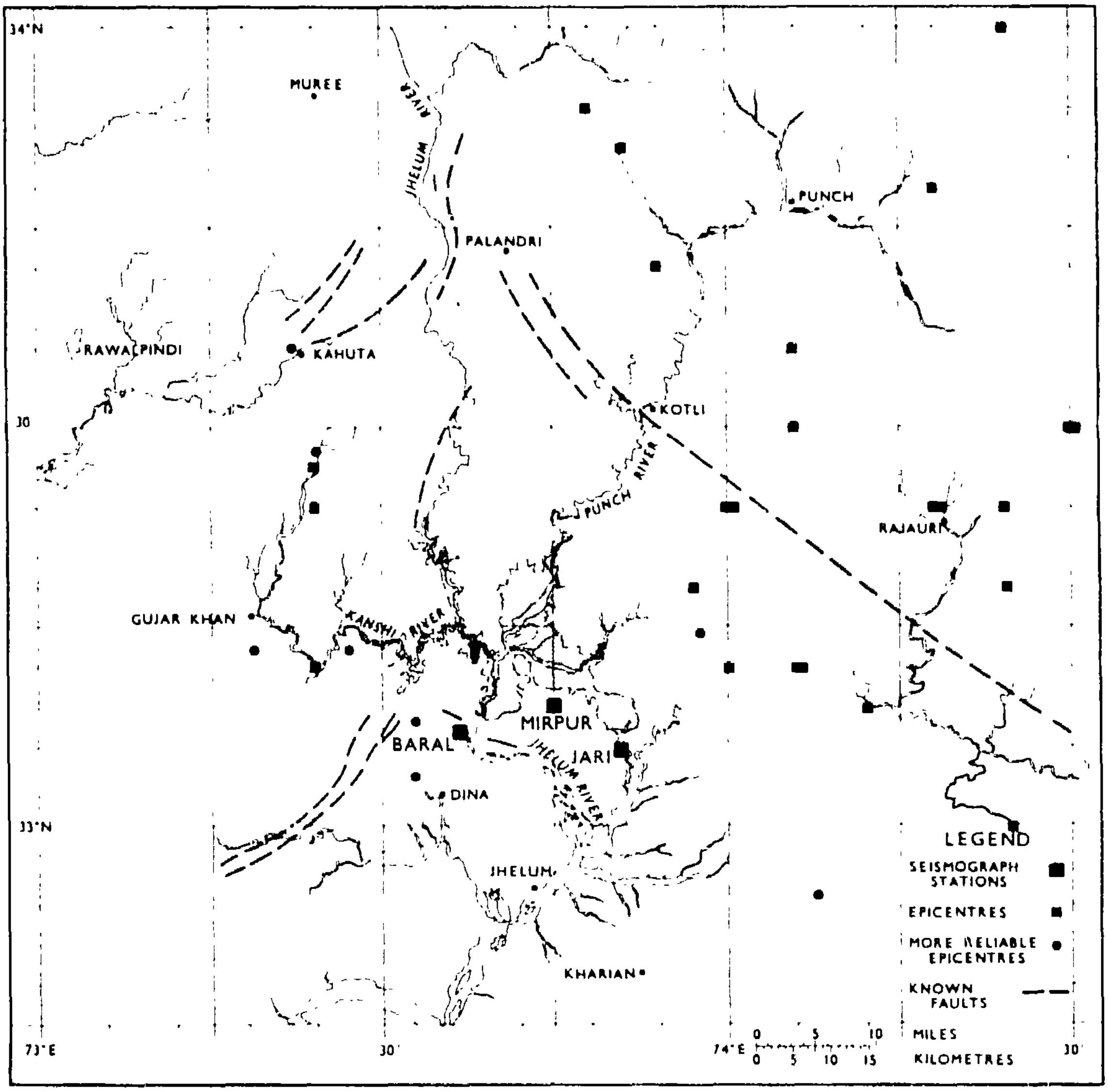
TABLE 1. EARTHQUAKES RECORDED WITHIN ONE DEGREE (111 KMS - 69 MILES) OF MANGLA

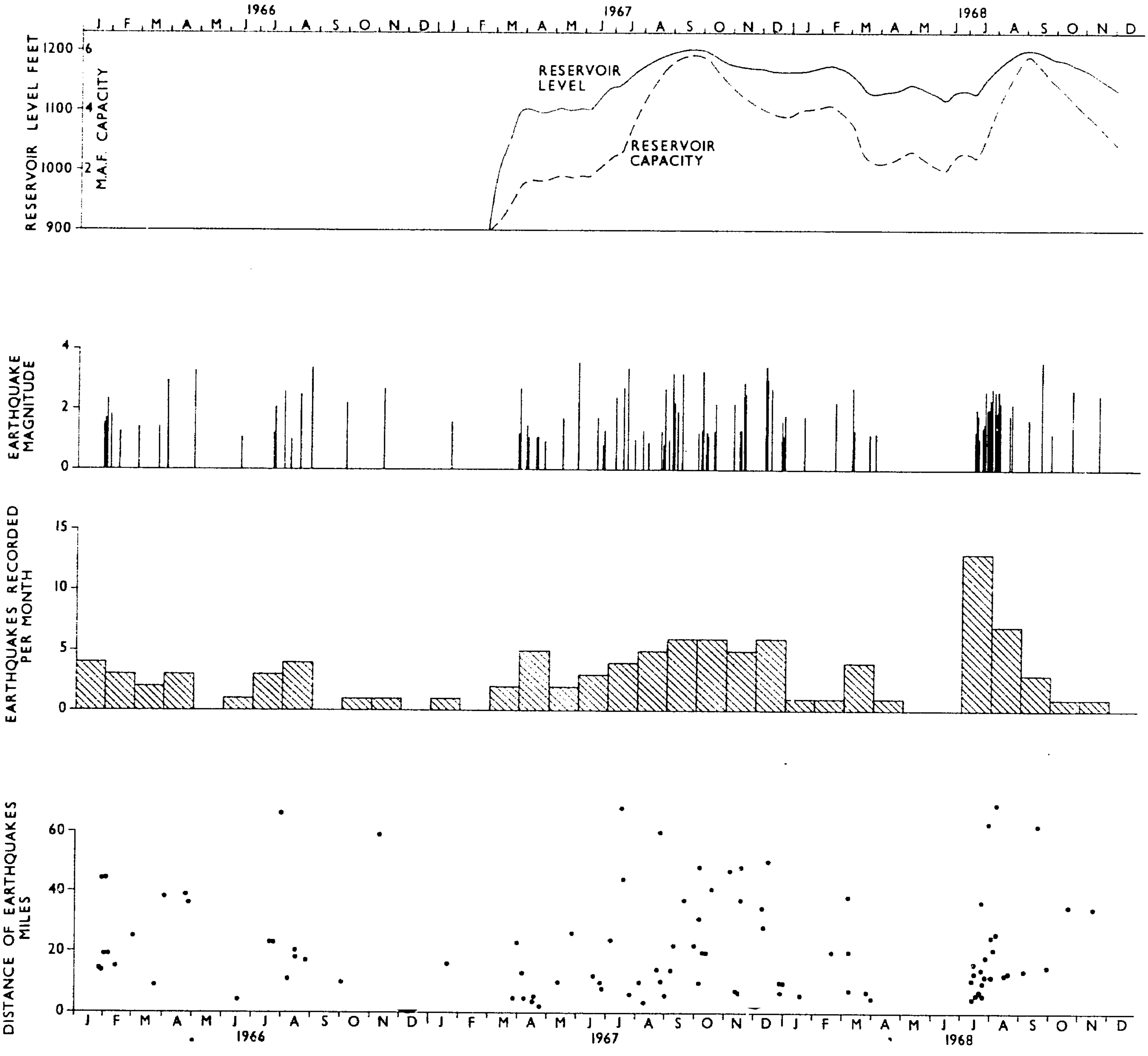
All positions given are approximate only, but those marked * are more reliable.
Times are given in U.T., which is 5 hours behind local time.

							Distance (miles)			
Year	Mon.	d.	h.	m.	s.	Mag.(M_L)	MIR	JAR	BAR	Approximate position
1966	Jan	28	00	04	22	1.5	14			
		28	00	30	43	1.7	14			
		31	22	59	48	2.3	44			
		31	23	40	44	2.3	44			
	Feb	04	22	06	04	1.8	19			
		04	22	47	03	1.8	19			
		13	13	58	28	1.2	15			
	Mar	02	23	11	31	1.4	25			
		23	22	01	17	1.4	9			
	Apr	02	20	19	35	2.9	38			
		25	22	29	09	3.5	39			
		29	21	02	26	3.3	36			
	Jun	17	18	29	08	1.1	4			
	Jul	20	00	55	29	1.2	23			
		23	22	56	51	2.1	23			
		31	18	09	11	2.6	66			
	Aug	07	03	26	29	1.0	11			
		16	07	02	43	2.4	20			
		16	14	22	00	2.5	18			
		28	22	16	05	3.4	17			
	Oct	03	06	52	17	2.1	10			
	Nov	11	22	09	52	2.7	59			
1967	Jan	19	01	31	17	1.6	16			
	Mar	28	10	19	39	1.2	5			Slip at Sanatha Kas.
		30	15	23	11	2.7	23			
	Apr	07	09	03	02	1.5	13			
		08	12	08	21	1.1	5			
		16	03	18	13	1.1	3 1/2			
		17	14	12	28	1.1	5			
		24	15	58	41	0.9	2			
	May	12	00	17	23	1.7	10			
		28	03	08	00	3.6	26	26		33.4°N, 74.0°E

Year	Mon.	d.	h.	m.	s.	Mag.(M_L)	MIR	JAR	BAR	Approximate position
1967	Jun	18	08	10	46	1.7		12		
		25	06	42	29	0.8		10		
		26	23	30	22	1.3		8		
	Jul	06	03	43	08	2.4		24		
		15	23	55	25	2.7	68	68		34.0°N, 74.4°E
		18	04	36	13	3.4	47	44	56	33.5°N, 74.5°E
		26	19	53	22	1.0		6		
	Aug	04	09	18	48	1.3		10		
		09	04	07	08	0.9		3 1/2		
		23	07	46	08	1.3		14		
		25	20	04	33	0.8		10		
		26	02	56	51	2.7	60	60		33.8°N, 74.3°E
	Sep	01	23	01	43	1.0		6		
		05	20	58	12	3.2	14	19	9	*33.22°N, 73.45°E Kanshi area
		05	21	11	06	2.2	22	29		33.4°N, 73.4°E
		10	00	29	08	1.9	35	22		33.4°N, 74.4°E
		14	00	26	35	3.2	37	37		33.6°N, 74.1°E
		30	22	54	43	1.2		12		
	Oct	05	06	52	27	3.0	52	48		33.5°N, 74.5°E
		05	14	04	45	3.3	31	31		33.5°N, 74.1°E
		05	18	42	48	1.3		10		
		09	19	03	38	1.2	23	20		33.2°N, 74.1°E
		09	19	13	07	1.1	23	20		33.2°N, 74.1°E
		17	18	41	07	2.1	41	44		33.7°N, 73.9°E
	Nov	06	21	16	09	2.2		47		
		13	00	12	47	1.3			7	
		13	01	40	05	1.3	7			
		16	00	01	44	2.5	41	37		33.3°N, 74.4°E
		16	12	38	06	2.9	48	53	53	33.85°N, 73.85°E
	Dec	10	17	51	30	3.5	37	34	47	33.4°N, 74.3°E
		11	02	24	17	3.0	28		25	33.45°N, 73.4°E Upper Kanshi River
		15	18	31	25	2.7	50	55		33.9°N, 73.8°E
		28	18	29	44	1.6		10		
		28	18	37	10	1.1		7		
		29	01	30	39	1.8		10		
1968	Jan	17	17	20	00	1.7		6		
	Feb	20	23	49	11	2.2	21	20		33.4°N, 74.0°E
	Mar	07	16	23	37	2.7	38	44	36	*33.60°N, 73.37°E Kahuta area
		07	20	17	10	2.5	20	26	13	33.2°N, 73.4°E
		08	18	31	11	1.3		7		
		24	20	28	47	1.1		7		

Year	Mon.	d.	h.	m.	s.	Mag.(M_L)	MIR	JAR	BAR	Approximate position
1968	Apr	01	22	53	48	1.2		5		
	Jul	12	07	23	50	1.3		11		
		12	09	30	48	1.0		5		
		13	18	19	32	2.0		16		
		14	07	12	01	1.8		13		
		16	16	46	21	1.0		6		
		19	04	33	12	1.4		17		
		22	20	19	09	1.5		14		
		23	07	28	53	2.6	30	36	27	*33.47°N, 73.40°E *Upper Kanshi River
		23	15	10	58	1.4		6		
		25	08	06	37	1.0		10		
		25	08	20	20	2.0	16	12		33.2°N, 74.0°E Kanshi area
		27	09	27	21	2.3		18		
		30	09	04	44	2.7	68	63	68	32.3°N, 74.1°E Gujrat area
	Aug	02	04	33	46	2.6	14	12	21	*33.24°N, 73.96° East of reservoir
		03	03	49	21	1.8	30	25	40	33.15°N, 74.2°E
		05	22	45	44	2.6	28	21	33	*32.91°N, 74.13°E South-east of reservoir
		06	16	59	46	2.1	26	32	19	*33.22°N, 73.31°E Gujar Khan area
		07	18	19	14	2.8	69	72		34.1°N, 74.0°E
		17	05	27	32	1.8	12	17	4	*33.13°N, 73.55°E Baral area
		19	06	58	58	2.1	13	17	5 1/2	*33.06°N, 73.55°E Baral area
	Sep	06	07	52	45	1.7	15	14		33.3°N, 73.95°E
		19	20	04	53	3.6	62	70		
		29	22	19	56	1.2		15		
	Oct	22	23	23	10	2.7	41	35		33.0°N, 74.4°E
	Nov	17	08	52	23	2.5	37	34	44	33.4°N, 74.3°E


34°N
MUREE
JHELUM RIVER
PALANDRI
PUNCH
RAWALPINDI
KAHUTA
KOTLI
30
PUNCH RIVER
RAJAURI
GUJAR KHAN
KANSHI RIVER
MIRPUR
BARAL
JARI
JHELUM RIVER
DINA
33°N
JHELUM
KHARIAN
73°E
30'
74°E
30'
LEGEND
SEISMOGRAPH STATIONS
EPICENTRES
MORE RELIABLE EPICENTRES
KNOWN FAULTS
0 5 10 MILES
0 5 10 15 KILOMETRES


1966
1967
1968
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
RESERVOIR LEVEL FEET
M.A.F. CAPACITY
1200
1100
1000
900
6
4
2
RESERVOIR LEVEL
RESERVOIR CAPACITY
EARTHQUAKE MAGNITUDE
4
2
0
EARTHQUAKES RECORDED PER MONTH
15
10
5
0
DISTANCE OF EARTHQUAKES MILES
60
40
20
0
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
1966
1967
1968