EARTHQUAKE INDUCED BY IMPOUNDING RESERVOIR
AND ITS INTENSITY FOR DESIGN OF DAMS

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SUMMARY

By the experience of some examples earthquake induced by reservoir impounding in China, engineers must distinguish between tectonic and depressive earthquake. Depressive earthquake is weaker and shorter than a tectonic earthquake in intensity and duration. The intensity of induced tectonic earthquake may be higher than the historical maximum earthquake. For the important dam design against earthquake, engineer might as well adopt 0.1 g as a criterion for check.

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In recent years several earthquakes induced by impounding reservoirs has happened in China. Up to now the available records have accumulated to 14 examples as shown in Table 1. Obviously, it is an unpleasent phenomenan with certain probability of occurrence which shoud be well considered in the design of hydraulic structures. How to consider the degree of risk and to select a resonable and economical designed intensity for large dams still remains a problem of serious concern. In this paper, we intend to discuss some major factors affecting dam design based on our own experiences.

1) In June 1980, an earthquake induced by impounding Reservoir of Wujiangdu project occured in Guizhou Province. Some colleagues have predicted such an earthquake event before impounding, especially in the region 4 km from dam site. People devoted in dam construction had paid more attention for this posibility. In view of the fact that only 400 M upstream of the dam, there is an unstable rock mass, Yellow cliff, if it collapes and slides down one day, it would be very dangerous for the dam. From this dam site up to the 3-4 km region of reservoir there are Cambarian, Permian, Triassic stratas with interplate limestone and shale, this strata is very steep, nearly perpendicular to the direction of river flow, formed by overturned folds. In the vicinity 1 km upstream of the dam, there is a fault being the largest in this area. It's direction is south to north extending to 60km along the strike of the folds. Yet its tectonite cements well. This implies that there is no remarkable movement in geological aspect after Mesozoic period. On the downstream of dam site there is limestone Triassic series, some karst caves have been formed 200 M under water. In this region water load reaches maximum, but it is not an epicenter inducing earthquake.

Main part of the reservoir 3-4 km upstream from dam, there is a wide flat synclinore. The valley developed along the axis of secondary anticlines folds, composes of Triassic series stratas. Whereas some placs on the bottom of valley

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Table 1

Sr. No.	Name of reservoir	Location: county	Location: province	Dam height (m)	Reservoir: volume ($10^6 m^3$)	Reservoir: surface area (km^2)	Reservoir: length along river (km)	Date of impounding	Epicentral region: location	Epicentral region: distance from dam (km)	Epicentral region: lithology	First discovered RIE: date	First discovered RIE: increment of water depth (m)	First discovered RIE: M_s	Maximum RIE: date	Maximum RIE: increment of water depth (m)	Maximum RIE: M_s
1.	Xinfengjiang (Hsinfenghiang)	Heyuan	Guangdong	105	13896	453.8		1959.10.	region A_1	0~6	Two cycle of granites	1959.11	10~20	micro	1962. 7. 29.	80	5.3
									region A_2	1~6 d.d.	granite, sandstone and shale, Meso-Cenozoic red bed	1962. 3.	75~80	micro	1962. 3. 19	75	6.1
									region B	12~26	granite, sandstone and shale	1961. 9.		micro	1962. 4. 5.		4.9
									region C	7~13	granite	1961. 10.		micro	1962. 3~4.		4.8
									region D	7~8	granite sandstone and shale	1962. 3	75~80	micro	1962. 7.	80	3.9
2.	Nanshui	Ruyuan	Guangdong	81.3	1218	39.4	21	1969. 2.	middle of north branch of reservoir	7	limestone thick-bedded	1969. 6	~22	micro	1970. 2. 26	~26	2.4
3.	Qianjin	Gucheng	Hubei	50	17	0.77	~2	1970. 5.	end of reservoir	~2	limestone dolomitic	1971. 10.	~0	micro	1971. 10. 20.	~2	3.0
4.	Zhelin	Yongxiu	Jiangxi	62	7171	387.4	127	1972. 1.	left bank of middle of reserv	28	limestone	1972. 10. 14	19	3.2	1972. 10. 14	19	3.2
5.	Huangshi	Cili	Hunan	40.5	612	47	16.5	1970.	end of two branches of reserv	12~14	limestone	1973. 5. 1	~0	1.0	1973. 7. 13	~0	1.3
6.	Fujiling	Huoxian	Anhui	74.4	488	23	25	1954. 6	outside of reservoir area,* west of dam and S-W side away from reservoir	10~12	marble	1954. 12. 14	~33 behind dam	(3~4*) intense [illegible]	1973. 3. 11	out of effect area of reserv water	4.5
7.	Danjiangkou	Junxian	Hubei	97	20900	816	101	1967. 11	Danjiang branch of reservoir: Songwan	37	limestone	1970. 6. 20	9	1.4	1973. 11. 29	18	4.7
									Danjiang branch of reservoir: Linmao Mt.	13	limestone	1970. 1. 15	43	1.2	1977. 8. 6	41	3.8
									Danjiang branch of reservoir: Yuhuang Top	17	Meso-Cenozoic red bed	1971. 4. 22	39	1.9	1971. 4. 22	39	1.9
8.	Nanchong	Shaodong	Hunan	45	155	<1	2.5	1967.	end and outside of reserv		limestone	1967 summ.	~0	voiced	1974. 7. 25	~0	2.8
9.	Shenwo	Benxi	Liaoning	50.3	790		12	1972. 11.	end of south branch	8	limestone thick-bedded	1974. 11. 18 **	<10	2.5	1974. 12. 22	<10	4.8
							29		middle of north branch	6~10							
10.	Zhengwen	Tainan	Taiwan	133	708	17	16.7	1973. 4.	high natural seismicity at the dam and reservoir area		Cenozoic sandstone and shale	seismic activity under the dam and reserv. basin is decreased after impounding					
11.	Xindian	Qianwei	Sichuan	26.5	29		5.7	1974. 4.	both bank of end of reserv.	4.2	limestone and rock salt	1974. 7. 16.	~0	2.5	1979. 9. 15	<10	4.2
12.	Wuxijiang	Quzhou	Zejiang	129	2060	41.9	54	1979. 1.	both bank of middle of reserv.	16	quartz syenite-porphyry	1979. 5. 23	0~10	<1	1979. 10. 7	28	2.8
13.	Wujiangdu	Xifeng	Guijhou	165	2300	47.8	76	1979. 11.	middle of reservoir: Jianjiaping and Xiaba	40	limestone thick-bedded	1980. 4. 19	~0	micro	1982. 9. 19	12	1.9
									middle of reservoir: Kanshi and Dongyang	21	limestone thick-bedded	1980. 3	27	micro	1980. 6	55	<1.0
									middle of reservoir: Qianpo	37	limestone thick-bedded	1980. 4. 19	15	micro	1980. 4. 24	25	<1.0
14.	Dengjiaqiao	Yidu	Hubei	12	0.4	<1	1.5	1979. 12.	west side of dam ***	0.5	limestone	1980. 8. 1.	<10	1.1	1980. 8. 1	<10	1.1

* It has not been agreed on whether there is RIE or not.

** There were 7 events in 1973~1974, located at the downstream, 10 to 25 km away from the dam. It seems to be the tectonic earthquakes.

*** At the exit of a karst underground river.

exposes Permian also. The rock mass inclines toward the bank of rivers, its dip angle being less than 30°. Fault structure seems to be less remarkable, yet a few large faults extending along the axis of anticlines, are less than 30 km, and cements well afterword. The limestone contains karst cave also and 3-4 stories of horizontal caves can be observed along both bank of the rivers. It's elevation coinsides with the river terrace and horizontal shale, which will be served as a water tight layer.

Around this reservoir, historical seismicity record shows once per ten years in average. The maximum magnitude is $M_m \leqslant 6$. But the depressive earthquake involved 40%. After impounding three river reaches have happened several times of filling earthquake. But in the region where limestone karst caves well developed no earthquake activity has been found. The relationship between water level and earthquake seems to be pretty complicated. Generally speaking, if water level higher than the entrance elevation of caves, a series of earthquake would appear immediately without any timelag. When water level draws down far below or submerges far above the cave entrance, no earthquake will be induced. At the main epicenter along Tiaodiapin and Xiaba village (Fig. 1) earthquake has been active only when the reservoir water level higher than natural water level 0-20 M.

Based upon this geological and seismologic condition, we have predicted the type of induced seismisity on Wujiangdu Reservoir is of depressive earthquake, the magnitude of which will never surpass the natural karst depressive earthquake (Ms = 4), and it would not give any remarkable influence to the Arch gravity Dam and the unstable rock mass in front of the dam as well.

In 1982 and 1983, water level in this reservoir is heigher than design normal water level but no recorded earthquake has been induced by impounding water.

2) Wuxijiang Reservoir in Zhejiang Province is located in a stable region. The earthquake intensity being 6°, and the dam is of buttress type in dam design, no engineering measures against earthquake has been taken into consideration. Impounding water began from Jan. 1979. In May of the same year, earthquake appeared in the middle part of the reservoir. In October, a bigger earthquake M_S = 2.8, the intensity of which being 5° at epicenter and a light damage occurred. Induced seismisity at this reservoir was unexpected the preliminary investigation shows that some aspects (rock and tectonic) are rather similar to Xinfengjiang Reservoir. Hence, some engineers worried about the safety of dam. (Fig 2)

Intensive studies have been made on seismic and geologic conditions as well as micro seismicity in this region. In history, no active fault and earthquake have been found. Zone of seismisity is far from the dam about 45-70 km, historical max. magnitude of earthquake is $5\frac{1}{4}$ - $5\frac{1}{2}$, the near by regional fault system located on the downstream west bank of river 15 km. This area has not been active after Cenozoic era. Dam and Reservoir site are upper Jurassic Massive acidic to intermediate volcanic rocks with flat stata, folds and fractures have not yet well developed. The direction of fault generally is on north north-east and north-east. Dip angle is near vertical and the length is less than 20 km. It's fracture is not large in extent, but well cementated. It proves that no active fault has been discovered. In the middle of reservoir there is a small seg basin, formed at late Jurassic. On Cretaceous series continental red sand-conglomerate rock and clay rock sedimented. On both sides discontinuecus faults have been found. During the Cenozonic era this rock with surrounding mountains elevated together, then eroded, and formed a landscape of eroded hill.

The epicenter of earthquake induced by impounding reservoir just located on the hill of south west along this Jurassic strata. Two small faults with direction north-east diped oppositly. Is it possible that they meet at depth 1.5 km underground. The epicenter has a linear distance 16 km, to the dam site when the impounding reservoir water just reached, and induced some small earthquakes immediately. The maximum earthquake magnitude after impounding water 9 monthes was M_L = 3.4 (M_S = 2.8). At this region depth of water was only 30 M. Every year when the level water reached a new elevation, a series of earthquakes were induced immediately without any timelag. If the water level was not higher than before, although water rose very fast and in large amount, the earthquake activity was not obviously. Now we have recorded more than 7000 events, most of which M_L = 0. It concentrated in an elliptical region, without any migration and diffusion, the area of which was 10 km^2 only. This fact can be explained by the water filtration through small faults and fractures from reservoir. At the upperstrata, some local stresses changed and induced earthquake by the micro crack of strata.

Therefore, we can conclude that the impounding water in reservoir would not induce intense earthquake migrating toward the dam. The maximum magnitude of earthquake at dam will be 3-3.5. The intensity of earthquake at dam site will not be higher than 6°. During flood season in 1983, reservoir full of water, water level higher than normal level 1.5 M. The depth of water reached as high as 65 M at epicenter region. Many small earthquakes frequently occurred around original epicenter yet the magnitude and intensity of earthquakes were not higher than before as predicted.

3) In view of the typical examples encountered, the geological condition seems to be most important factor to predict earthquake induced by impounding reservoir. But the understanding of the mechanism and real cause of such phenomenon still remains a difficult question, nevertheless the depth of epicenter is usually not so large. Hence, the method of comparism of seismic geology is pretty acceptable to meet the requirement of dam design.

We use 60 typical cases of earthquakes impounding reservoir for preliminary analysis. The result shows, that it can be devide into two categories of earthquakes: One is of tectonic (inner stress) earthquake, and the other is of depressive (outside force) earthquake, including those due to landslides or freezing fractures etc.

The composition of rock types, hydrological geology as well as tectonic conditions is quite diversified. We hereby recommend to distinguish different categories of earthquake induced by impounding reservoir according to geological environments as shown in Table 2.

4) Attention is focussed on the study of earthquake induced by reservoir impounding of tectonic type. Earthquake of magnitude 4.5 to 5 or even stronger are in general the tectonic type, because the exogenic geological processes cannot accumulate so great amount of the strain energy. Only the

Table 2

Type and Subtype of Geological Environments of RIE	Possible Magnitude of RIE
Type I: Soft rock masses	No RIE will occur
Type II: Rock mass with cracks a. Subtype of massive rock with cracks	micro or weak earthquake
b. Subtype of layer rock with cracks	mainly micro earthquake
Type III: Rock mass with tectonic fault a. Subtype of massive rock with tectonic fault	medium or strong
b. Subtype of layer rock with tectonic fault	weak or medium
Type IV: Karst Strata a. Subtype of karst strata with cracks	micro or weak
b. Subtype of karst strata with techonic fault	weak or medium

moderate and above mentioned earthquake induced by reservoir impounding can bring considerable damages to dams. Among the 112 cases of earthquake induced by reservoir impounding, reported all over the world, 29 are moderate (Ms=4.5 to 5.9) and 4 are strong ones (Ms $\geq$ 6.0). Both account for 29.5% of the total cases of the earthquake induced by reservoir impounding; while in China 28.6% is the corresponding proportion which cannot be neglected by dam constructors.

Some one voiced their oppinions that the intensity of earthquake induced by reservoir impounding does not need to be taken into consideration independently, because they estimate that the intensity of earthquake by reservoir impounding goes beyond neither the basic intensity nor the maximum historical earthquakes. This argument would be ill grounded in facts. There are a lot of recorded earthquake datum in China which cover one or two thousand years and in some seimic zone were discovered 2 to 4 earthquake active and quiet cycle which lasted hundreds of years. However they are too short in comparison with geological process and can not be regarded as the reliable bases to predict maximum earthquakes in the future. If has been proved by the recent study of paleoseismology which made the discovery that in some zones where earthquakes rarely occurred during the last decases there are traces of strong shocks whose period of reoccurence has been thousands of years or even more.

It has been proved by the study of earthquake induced by reservoir impounding that many strong shocks tend to occur in the microseism or non-seism region such as Xinfengjiang in China and Koyna in India. The information listed in Table 3 shows that the intensity of earthquake induced by reservoir impounding of the tectonic type tends to surpass the basic seismic intensity (equal to one event per 100 years) and maximum historical earthquake (equal to one event per Thousand years) in the some region. Therefore the effects caused by earthquake

Table 3

Name of Dam	Natural Earthquake Before Impounding		RIE		Basic Intensity *	
	Maximum historical Earthquake Near Reservoir Site (Ms)	Epicentral Intensity	Main Earthquake (Ms)	Epicentral Intensity	Before Building Reservoir	Revised After RIE
Xinfengjiang	4**	<6	6.1	8	6	7
Shenwo	No Earthquake		4.8	6	6	7
Danjiangkou	>3.0	<5	4.7	7	7	7

* Which is more or less equal to the maximum intensity of the earthquake which may occur in the coming a houndred years.

** The maximum earthquake (Ms=6) recorded in Heyuan Shavowu fault zone which is the river Xinfengjiang occurred 200 km away from the reservoir in Huichang, Jiangxi Prov. in 1806. The record of the strong earthquakes in Guangdong and Jiangxi Prov. began in 1045.

induced by reservoir impounding must be taken into consideration independently as a factor in the earthquake-resistant design for the dams where the possibility of the stronger earthquake induced by reservoir impounding of the tectonic type has been proved before impounding by seismogeological investigation. The reliable and and systematic methods have not been developed so far to predict the maximum magnitude of earthquake induced by reservoir impounding of the tectonic type. The comparison between the geological and seismic conditions of the dam and reservoir area and the similar conditions of the known earthquake induced by reservoir impounding or the natural earthqauke is preferable. A relatively precise data can thus be picked out which may reach Ms = 6.5 or more. 0.1g may be used as a check for the resistance of dams to earthquakes in case of the disadvantage of geological conditions and the lack of compartive data so as to quarrantee the safty factor as well as less experience cost of dam constructions.

5) The statistical datum shows that only 10% of the dams higher than 100 m experienced induced seismicity of which 70% are microseisms and weak seisms. Therefore would be unreasonable in cost to design dam projects according either to intensity 7 to 8 or to the maximum earthqauke induced by reservoir impounding recorded in the world regardless of varieties of geological conditions.

Most of the microseisms and weak seisms fall under the category of exogenic processes. Discussion will be extended to depressive earthquakes in karst regions. It has long been found out that a lot of epicenters of earthquake induced by reservoir impounding are located in the well developed karst region. Of the 69 events of earthquakes with geological datum across the world, 32 are located in region with carbonate rocks, making up 46.4%. Of the 14 events in China, 11 in karst regions, making up 78.6%. What Figure 3 shows is a statistics according to magnitudes. Attention should be focussed on the double peaks of distribution curve, one is $M = 4.5$ to 4.9, the other being $M < 3.0$. Taking the China events for example, there is a regional fault zone of over 200 to 300 km through each epicenter of the 3 earthquakes of $M = 4.5$ to 4.9, where as there is only a small fault through the epicenter of the 7 earthquakes of $M < 3.5$, where the karst has well developed. Evidently earthquake induced by reservoir impounding in Karst region falls into two different genesis types, belonging respectively to IVa and IVb as listed in Table 2. Evaluation of earthquake induced by reservoir impounding of the karst tectonic type is the same as that of earthquake induced by reservoir impounding of the general tectonic type, but sometimes with exceptions in which occurence of a few strong earthquakes such as Kremasta in Greece having the geological conditions of the karst crack type, as in Wujiangdu mentioned above, inducing only microseisms and weak seisms which in general would not cause serious damage.

Other seismic effects caused by exogenic geological processes as well as the earthquakes occuring in the geological conditions listed in IIa and IIb (Table 2), as in Wuxijiang above, are mostly microseisms and weak seisms which, on the whole, need not be taken into account independently with the exception of those occuring close to dams, which can be checked in design using 0.1g as a criterion.

According to the conventional theory of pore pressure or the theory of reservoir loading, the occurence of earthquake induced by reservoir impounding is due to the fact that there is a certain amount of surcharge water head (dam height) or reservoir loading reservoir capacity. Hence, up to now when dam height 100 m and/or reservoir capacity $\geq 10^9$ m^3, it will be universally adopted as the criterion according to international whether the study of earthquake induced by reservoir impounding should be conducted. But there are two problems in the past statistic information: 1. The surcharge water head in the epicenter is replaced by dam height or water level of the dam reservoir. 2. The surcharge water head during the earthquake inception is replaced by the water head during the maximum earthquake (dominant earthquake). In this case, the effects of dam height and the reservoir capacity are overstressed. Figure 4 shows the relation between the water head in the epicenter area during the incipient earthquake and that during the main earthquake in China. It can be seen that in most cases, the incipient earthquake often occurs immediately after the biginning of impounding i.e. when the amount of impounded water is not large enough and the surcharge water head in the epicenter area being less than 20 m. Although the dam height in some events is over 100 m microseisms are induced, when the reservoir water level just surpasses the water level during natural flood in epicenter area. Even main earthquakes occur mostly not in the deep water dam reservoir where both the water head and the amount of settlement are the maximum, but in the middle and end reaches of the reservoirs where water depth is less than 40 to 50 m. It can be seen that there is no straight forward relationship between earthquake induced by reservoir impounding and the water head and the reservoir capacity. Earthquake induced by reservoir impounding depends mainly on the particular complex of lithological, tectonical and hydrogeological conditions in the vicinity of reservoir area. Covering different tectonic provinces and various lithological areas, big reservoirs with high dams usually encounter much higher probability of complex of bad geological conditions. That might be possible one of the reasons why the percentage of occurence of the induced earthquake of big reservoir with high dam is higher. Therefore, dam height and/or reservoir capacity cannot be regarded as the only criteria of whether earthquake induced by reservoir impounding should be studied or not.

6) Conclusion:

(1) It must not be ignored that different mechanisms of earthquake induced by reservoir impounding relate to lithology and tectonics. A strict distinction should be drawn between tectonic and depressive earthquake.

(2) If earthquake induced by reservoir impounding were of tectonic fault earthquake, its intensity tends to be higher than that even recorded. Bigger earthquakes are easier to be triggered especially when stress in strata concentrates. Therefore the design intensity should rest on detailed geological exploration.

(3) The important factor inducing are neither water depth or increased load but the size of the reservoir and water surface area.

(4) The check of design intensity of earthquake induced by reservoir impounding should be considered from the hydraulic engineering itself avoiding excessive expansion of the engineering construction work as much as possible. 0.1g can be considered as a certain criterion for check when designs are of important projects.

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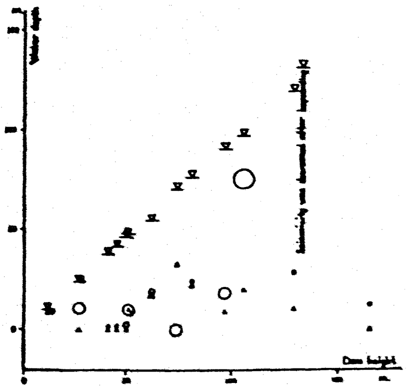

Fig 4 Relationship between dam height and water depth of preliminary and main shocks
⊻ Upstream water depth at dam ; △ Water depth of preliminary shocks at epicentral region ; ○ The same of main shocks ; ○ The same but in dispute ; ▲● M_L > 3.0 ▲○ 3.0–3.9 ; ○ 4.0–4.9 ; ◯ M_L > 6.0

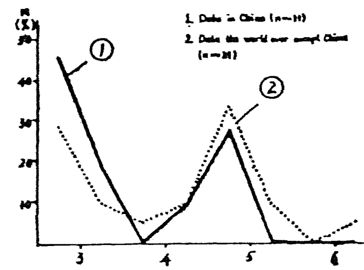

Fig 3 Distribution of RIE in areas of carbonate rocks by their magnitude

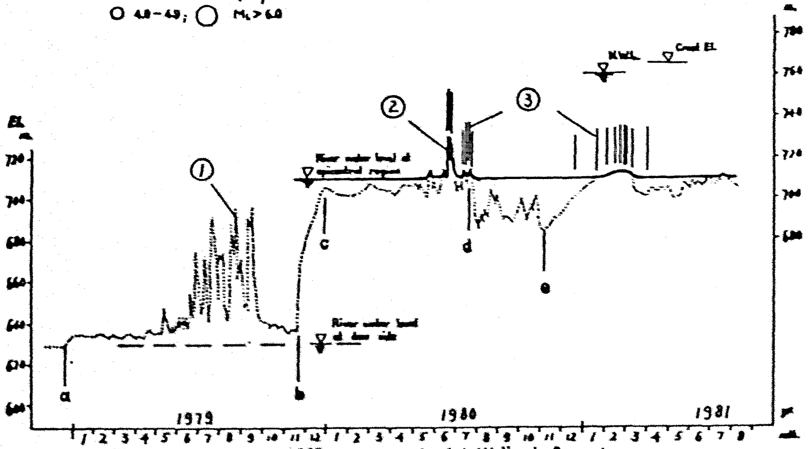

Fig 1 Correlogram of the RIE with water level in Wujiangdu Reservoir
a. Closing of diversion tunnel ; b. Closing of gate for storage ; c. Power generation ; d. Reservoir drawdown for maintenance ; e. Refilling of reservoir ; 1. Hydrograph of water level at upstream dam surface ; 2. Water level hydrograph at epicentral region ; 3. Seismic events.

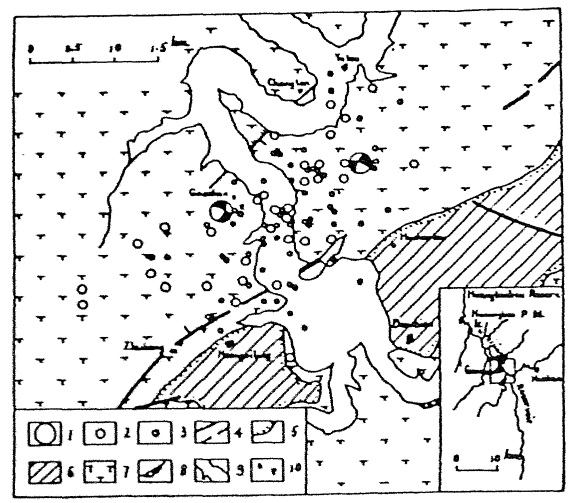

Fig 2 Epicentral region map of Wuxijiang RIE
1–3 Epicentre (1— 3.9 ≥ M_L ≥ 3.0 ; 2 — 1.9 ≥ M_L ≥ 1.0 ; 3 — 0.9 ≥ M_L ≥ 0.0) ; 4 — Fault and suspected fault ; 5 — Unconformity line ; 6 — Cretaceous red sandstone, conglomerate and clay stone ; 7 — Upper Jurassic effusive rocks ; 8 — Rock fall mass ; 9 — Reservoir area ; 10 — Population centre