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SYNOPSIS : In April of 1983, a sequence of earthquakes were recorded by the National Seismic Network where the epicenters were located in the upper reaches of the Srinagarind Reservoir. A detailed evaluation of these earthquakes have been initiated since that time. Network of micro seismic instruments have also been installed in the region in order to establish the capability of higher resolution for seismic parameters and allow the greater understanding of the mechanism of the activity.

After seven years of monitoring and data collecting, analysis of the results have been performed. Results obtained from the evaluation of overall characteristic seismicity, including the review of world wide data on the seismic, geologic and characteristics of reservoir triggered seismicity (RTS) ensure us to accept the high possibility of reservoir induced seismicity phenomena.

INTRODUCTION

The Srinagarind Dam is a multipurpose project located on the Quae Yai River, Kanchanaburi province, about 190 kms. northwest of Bangkok. It is one of the largest hydroelectric projects in Thailand which serve to provide electricity, irrigation, water supply, salinity control, flood control, fishery improvements and tourism development.

The Dam is a compacted rockfill claycore type of 140 m. high and 610 m. long with a curved axis crest. The construction was commenced in early 1974 and completed in March 1980. The reservoir created by the dam has the surface area of 420 square kms. with total capacity of about 17,000 MCM. (million cubic meter) at full supply level. The initial filling started in August 1977 and reached its first maximum level at elevation 176.62 m.MSL (mean sea level) in November 1982 with 3.38 m. below the retention water level.

In April of 1983 there has been a series of earthquakes located in the upper reaches of the reservoir, around the confluence of Quae Yai River, Huai Mae Phlu and Huai Kha Khaeng. This epicentral area are about 60 kms. north of dam site. The main shock on April 22, 1983 was preceded by a foreshock sequence within one week and was followed by a long aftershock sequence. The main shock was 5.9 ML. while the largest foreshock and aftershock were both 5.3 ML. Especially the events larger than 5 ML. were felt over a large part of western and central Thailand. Minor damages were reported in Bangkok and their vicinities where such an earthquake is quite unusual and the area has been previously considered as aseismic. From these earthquake events, three local seismic stations were installed in the vicinity of Srinagarind reservoir with the technical assistance of EBASCO Overseas Corporation (U.S.A.).

The earthquake sequence that began in April of 1983 was the first ever recorded seismicity in this area. The effects of these events as reported by residents around the reservoir are including of a probable seiche in the epicentral area, the strong shaking of trees, loud rumbling and booming noises, rockfalls and small scale landslides. Rockfalls are common in the epicentral area and extend up the northwestern arm of the upper reaches of the reservoir. Most of rockfalls were failures of steep to vertical limestone faces, however, a few landslides of soil materials were observed on the reservoir rim.

In addition, the surface rupture and sinkholes collapse were also reported just to the south of Huai Mae Phlu. This rupture is very straight and crosscuts existing topography and stream drainages. This feature trends approximately N 75 - 80 W, and is about 4 kms. long, where the crack crosses soil materials, vertical offsets up to 20 centimeters were observed, with the north side up relative to the south side. No evidence of lateral motion has been found. The pre-existing joints in granite bedrock which trend approximately N 80 W to E-W were opened locally with maximum opening of 6 cms. A few cases of sinkholes collapse have been found at the location of about three kilometers south of the rupture area. This phenomena is the commonly feature of strong ground shaking in the karstic areas. These observations indicate the typical features associated with moderate to large earthquakes that occurred at shallow depth.

GEOLOGY AND STRUCTURE OF THE SRINAGARIND PROJECT REGION

The rock foundation of the project area is underlain by all types of rock, metamorphic, sedimentary and igneous. The meta sedimentary sequences of Precambrian and early Paleozoic are noted to be the older units, while the younger ones are made up with upper Paleozoic and Mesozoic sequences and the semiconsolidated to unconsolidated Cenozoic sedimentary rocks. These rocks were intruded and covered in part by the igneous rocks. There is a distribution of pure limestone showing prominent karstic phenomena on the right bank of the reservoir, as exposed above the reservoir level.

The geology of the dam site consists of Paleozoic clastic sediments of Kanchanaburi series (Silurian to lower Carboniferous) and is comprised of calcareous sandstone, quartzite, shale and thin layers of limestone. Within the dam foundation, three significant faults have been found as located at the lower left abutment, the river bed and the right abutment. The fault at the river bed is about 10 m. wide, containing soft decomposed fault breccia while the others are about 1 m. wide. However, the fault on the lower left abutment is strongly sheared and weathered, and is considered to be the worst portion which require careful treatments. These three faults are considered as inactive and do not create any serious problems to the foundation of the dam.

RESERVOIR GEOLOGY

The main part of the Srinagarind reservoir area cover about 60 kms. long, occupies a north-south trending basin filled with Tertiary to Pleistocene deposits. The Tertiary rock sequences are essentially semiconsolidated conglomerate and pebbly sandstone with a few thin sub-bituminous coal seams, overlain by the Quaternary unconsolidated sediments of colluvial soils, river terrace and alluvial sediments. The basin is believed to be fault-bounded, but the border faults are buried beneath the sedimentary fill.

The upper reaches of the reservoir, however, cross into the older basement terrain consisting of Paleozoic clastic sediments and limestone, intruded by granites of Mesozoic age. The area appears morphologically old, with rounded mountains and ridges of granite, quartzite and argillaceous limestone. Massive limestone units form cliffs and escarpments in some part of the areas. The overall structure is characterized by northwest trending ridges and valleys. Several faults, both observed and inferred, have their trends being parallel to the regional fold axes. Their orientation and relationship to local geology suggest that they formed in association with the folding and are considered inactive. Interpretation of remote sensing satellite imagery (LANDSAT) and aerial photos indicates the major structural grain of this area is north-northwest with a few east-west and northeast linear features.

SEISMICITY AND MONITORING NETWORK IN TH PROJECT REGION

The western part of Thailand, where Srinagarin dam is located, has been considered as aseismi area. The closest seismic active zone in thi region are the Alpide subduction zone wher large earthquakes were felt in the western par and central plain of Thailand. The epicenter of those quakes were identified and locate further west off-shore or even in Myanma (Burma).

Following six years since the initial impoundment, a sequence of earthquakes began in th upper reaches of the Srinagarind reservoir. The mainshock of 5.9 ML occurred on April 22 o 1983. Foreshocks and aftershocks associate with this earthquake were recorded by 7 loca seismological stations, of which the closes station is located 60 kms. southwest from th epicentral area. Review of pre-instrumenta and instrumental seismicity of Thailand an surrounding regions indicates that the present events occurred in an area that has not experienced moderate to large earthquakes in th recent geologic past. The characteristics o this seismic activity suggests that it wa triggered by the impoundment of the reservoir.

Three strong motion accelerographs (SMA-1) ha been installed in Srinagarind dam since 1979. These three units are electrically interconnected and on standby operating condition. Of the main event only two accelerograms from the left abutment and the dam crest were obtained, while another accelerograph at the dam toe was out for repair and back in place after the mainshock. The ground accelerations obtained from these two accelerograms were rather low, about 0.02 g to 0.03 g in the upstream - downstream direction. The dam performed very well and showed insignificant effect from these earthquakes.

The network of micro seismic instruments has been recommended by EBASCO Overseas Corporation to install in the region in order to establish the capability of higher resolution in the epicentral locations and allow the greater understanding of the mechanism solution and distribution of the seismic activity.

In February, 1985, 3 seismic stations were installed in the vicinity of Srinagarind Reservoir and as the integral part to the other 7 seismic stations of the nearby Khao Laem Dam. The location of these stations are shown on Figure 1. Each of the station consists of a vertical seismometer and smoked paper drum recorder. The network is capable of detecting local microseismic events of less than 1.0 ML throughout most of Srinagarind reservoir area.

During the period of 1985 through 1990, a total of 37 events of magnitude 3.0 or above and 134 events of magnitude 2.0 or above were recorded. The largest event recorded was a 4.5 ML on March of 1985. Most of the events recorded at Srinagarind reservoir occurred near the confluence of Quae Yai river and Huai Mae Phlu, as illustrated in Figure 2, the same epicentral area of the 1983 events. The overall efficiency of the network was excellent and proved to be useful to better define the location and distribution of the continued seismicity in this area. The data obtained from local seismic network indicate that the continued seismic activity is concentrated in the same area where the events of the April 1983 were located, especially along Huai Mae Phlu, the southeast extension.

EPICENTRAL DISTRIBUTION

Review of epicenter locations published by the Thai Meteorological Department (TMD.) indicates the activity is spread throughout the area and does not tend to define linear or planar zones for a seismogenic structure. Moreover the distribution of activity is not consistent with field observation that define a much smaller epicentral area on the basis of surface effects. A total of 27 events occurring in April of 1983 were relocated using computer program HYPO 71 for earthquake relocation and the phase arrival times published by the TMD. The relocation of epicenters defines a northwest trending zone along the northwest arm of the reservoir and extends to the south along Huai Mae Phlu to the area of surface rupture, which is corresponded to the area of greatest surface effect as shown in Figure 3. Seismic activities have been continued up to present with lesser frequency.

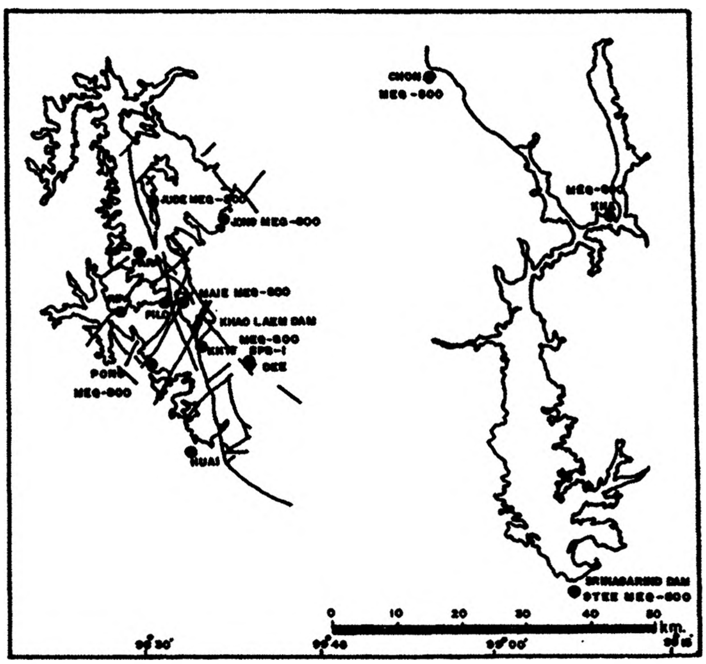


Figure 1 Micro Seismic Network for Srinagarind and Khao Laem Dam

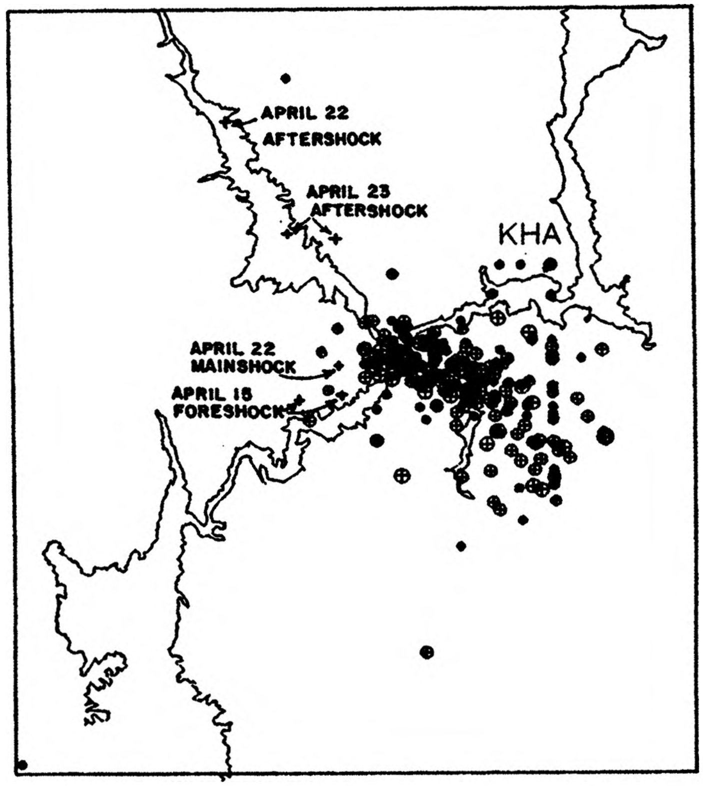


Figure 2 Epicentral Distribution of The Continued Seismicity in The Srinagarind Reservoir

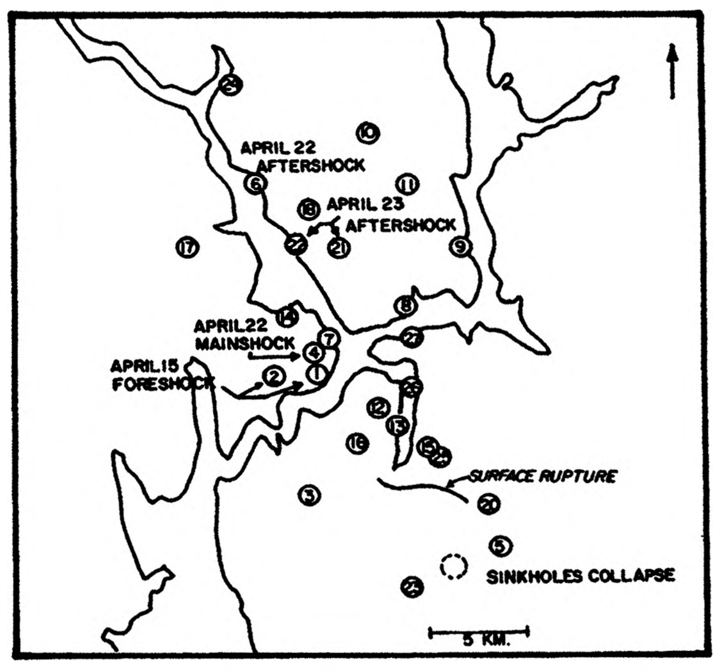
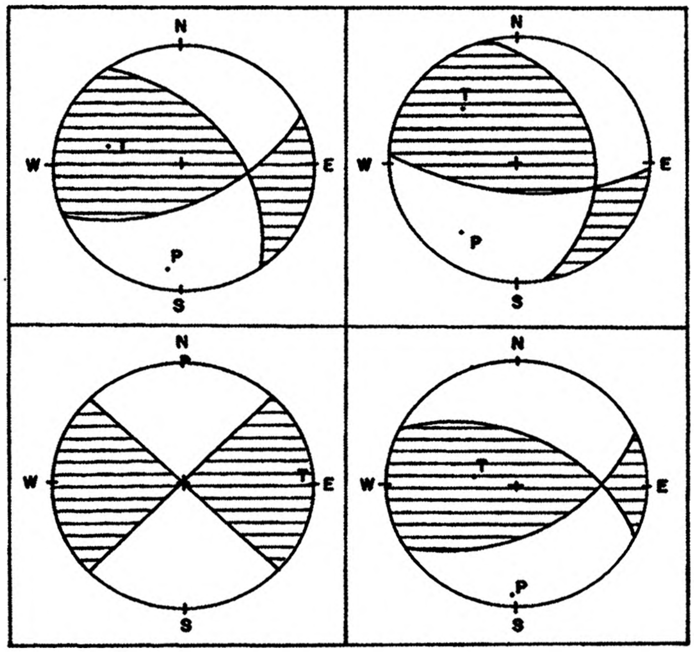


Figure 3 Epicenter Relocation of April 1983 Earthquakes

FOCAL MECHANISM

Six earthquakes of the April, 1983 sequence were large enough to be recorded and located by stations of the World Wide Standardized Seismic Network (WWSSN). The USGS has published the preliminary determination of epicenters and focal mechanism solution for the main shock of April 22, 1983 which indicate predominant reverse faulting with two nodal planes, one strikes to the northwest with a dip to the northeast and the other strikes northeast with a dip to the southeast, as shown on Figure 4.

April 22, 1983; 5.9 ML
USGS EBASCO



March 10, 1985; 4.5 ML EBASCO   May 28, 1990; 4.2 ML EGAT

Figure 4 Focal Mechanism Solutions for Srinagarind Events

The USGS considered the northwest trending nodal plane as the preferred fault plane with the focal depth of approximately 10 kms. This preferred fault plane is coincided with the distribution of the epicenters relocation, but it is not consistent with the east-west surface rupture found after the main event.

The composite focal mechanism solution of the main shock on April 22, 1983 have also been performed by EBASCO using the P and S-wave data obtained from NOAA. The result suggests the N 80 W trending steeply dipping nodal plane as a preferred fault plane. The type of motion indicated is reverse faulting with a small component of left lateral motion as illustrated in Figure 4. These data, therefore, may represent activity along two or more faults in the area, one fault trending east-west with reverse motion which is consistent with the surface rupture while movement along northwest trending fault would occur as right lateral strike slip motion which represented by the distribution of epicenters.

The continuing activity in this area have been recorded by the local seismic network. The most significant activity occurred in March of 1985. During that period, over 200 events were recorded and the largest event of this swarm was the magnitude 4.5 ML. The epicentral distribution of this seismicity and focal mechanism data for the magnitude 4.5 ML. and its aftershocks suggest that much of the activity occurred along a northwest trending structure with the right lateral motion. This suggestion is well consistent with the magnitude 4.2 ML. event which occurred on May 28 of 1990. The epicenter location and the focal mechanism solution of this event also indicates the northwest trending fault plane with small component of right lateral motion as shown on Figure 4. All data collection, analysis of results and focal mechanism solutions suggest the presence of a northwest trending causative structure. The east-west surface rupture discovered following the main event of April 22, 1983 is modeled as a reverse fault marking the southern end of the reactivated segment of this feature (EBASCO 1985)

EVALUATION OF SEISMIC PARAMETERS

An aspect of evaluation of Srinagarind seismic parameter was on the characteristic feature of "Reservoir Triggered Seismicity" (RTS). The characteristic features investigated for these earthquakes are; the slope in the frequency magnitude relation, the magnitude ratio of the largest aftershock to the mainshock, and foreshock-aftershock patterns. These characteristic features of earthquake reflect upon the mechanism structure of the media and the nature of the applied stress.

THE FREQUENCY-MAGNITUDE RELATIONSHIP

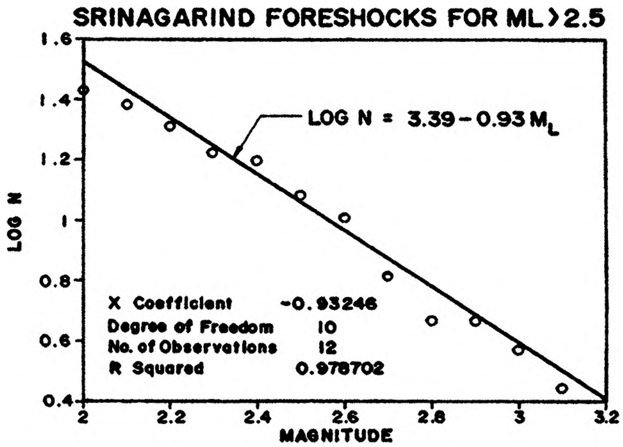
Evaluation of the frequency-magnitude distribution for the Srinagarind earthquakes was made by using a cumulative number of earthquake with a given increment of magnitude. By limiting the earthquake analyzed to the events of magnitude greater than 2.0 ML. Recorded data of 31 foreshocks and 260 aftershocks were used for evaluation purpose. The linear relation between log N and M were obtained as follows:

Foreshock : $\text{Log } N = 3.39 - 0.93\,M$

Aftershock : $\text{Log } N = 4.43 - 0.79\,M$

Where N is the accumulated number of events, and M is the local magnitude in richter.

The slope b-values for Srinagarind earthquake are 0.93 and 0.79 for foreshock and aftershock as illustrated in Figure 5. Eventhough the b-values for RTS are mostly > 1.0 (Gupta 1976). But the Srinagarind b-values are much higher than those for the natural earthquake. Another reason that differentiate the RTS from natural earthquake is the foreshock b-values lower than the aftershock b-values for the natural earthquake (Berg 1968) which is reverse for the RTS events. The b-values for RTS and natural earthquake are listed in table 1 below.



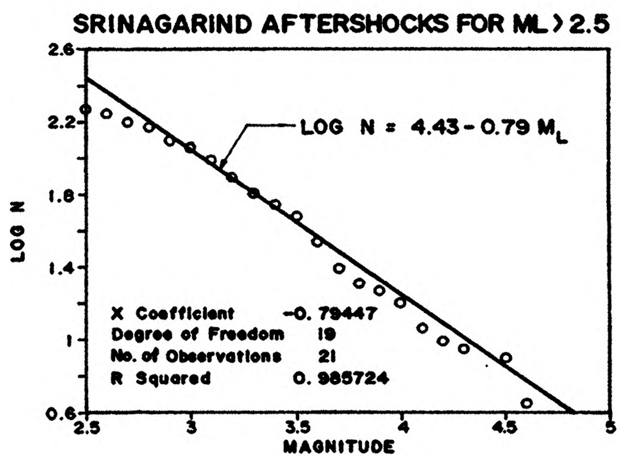


Figure 5 Illustrate Relationship between Log N and Earthquake Magnitude for Srinagarind Data on Foreshocks and Aftershocks

TABLE 1 Comparison of the b-values for Reservoir Triggered Seismicity and Natural Earthquake in the Same Regions.

Dam/Region	No.of Quake	Magnitude range	b-value Fore-shock	b-valve After-shock
Kariba Dam. (Africa)	1405	2.0-5.8	1.18	1.02
Africa region.	43	3.2-5.6	-	0.53
Kremasta Dam. (Greece)	3320	2.0-5.6	1.41	1.12
Kremasta region.	-	-	-	0.64
Koyna Dam. (India)	573	2.8-5.2	1.87	1.09
Godawari Valley	52	2.1-5.7	-	0.51

(-) For the case of natural earthquake phenomena, b-value of foreshock cannot be obtained.

RELATIONSHIP BETWEEN THE MAGNITUDES OF THE MAINSHOCK AND THE LARGEST AFTERSHOCK.

The difference between the magnitude M0 of the mainshock and the magnitude M1 of the largest aftershock for Srinagarind earthquake, M0-M1 is 0.6 and the ratio of the two magnitude M1/M0 is 0.90. Furthermore it has been observed that M0-M1 is about 1.2 for the large and shallow natural earthquake (Bath's 1965) which clearly differentiates from the world wide cases of RTS as listed in table 2.

TABLE 2 Comparison of world wide earthquake data for reservoir triggered seismicity with Srinagarind and Khao Laem Dam

Dam	Main Shock (M0)	Largest After Shock (M1)	M0-M1	M1/M0 after-shock	b-valve fore-shock
Lake Mead	5.0	4.4	0.6	0.88	1.40
Kariba	6.1	6.0	0.1	0.98	1.02
Kremasta	6.2	5.5	0.7	0.89	1.12
Koyna	6.0	5.2	0.8	0.83	1.12
Srinagarind	5.9	5.3	0.6	0.90	0.93
Khao Laem	4.5	4.1	0.4	0.91	1.25

FORESHOCK-AFTERSHOCK PATTERNS

The foreshock-aftershock pattern obtained from plotting the frequency distribution per unit time of both the foreshocks and aftershocks. As seen in Figure 6 the mainshock at Srinagarind earthquake was preceded by many foreshocks and followed by a large number of aftershocks. It could be seen that the foreshock-aftershock pattern for these earthquakes corresponds to type 2 of Mogi's classification (Mogi's 1963) which most of the RTS's pattern fall into either type 2 or type 3 of this Mogi's model.

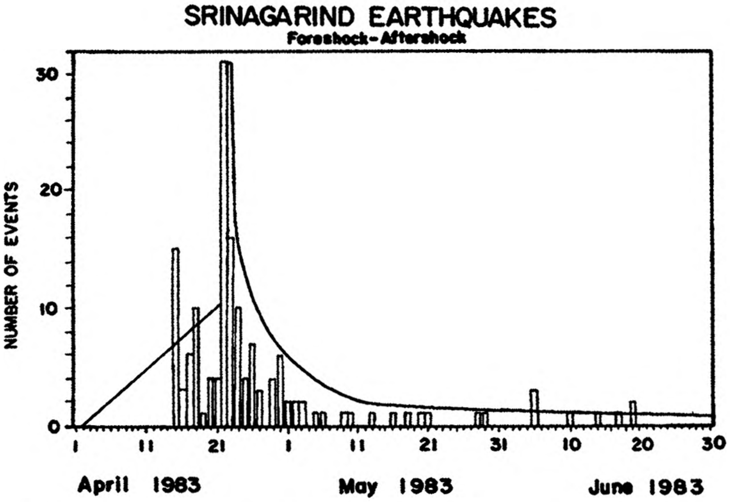


Figure 6 Foreshock-aftershock Pattern for The Srinagarind Earthquake.

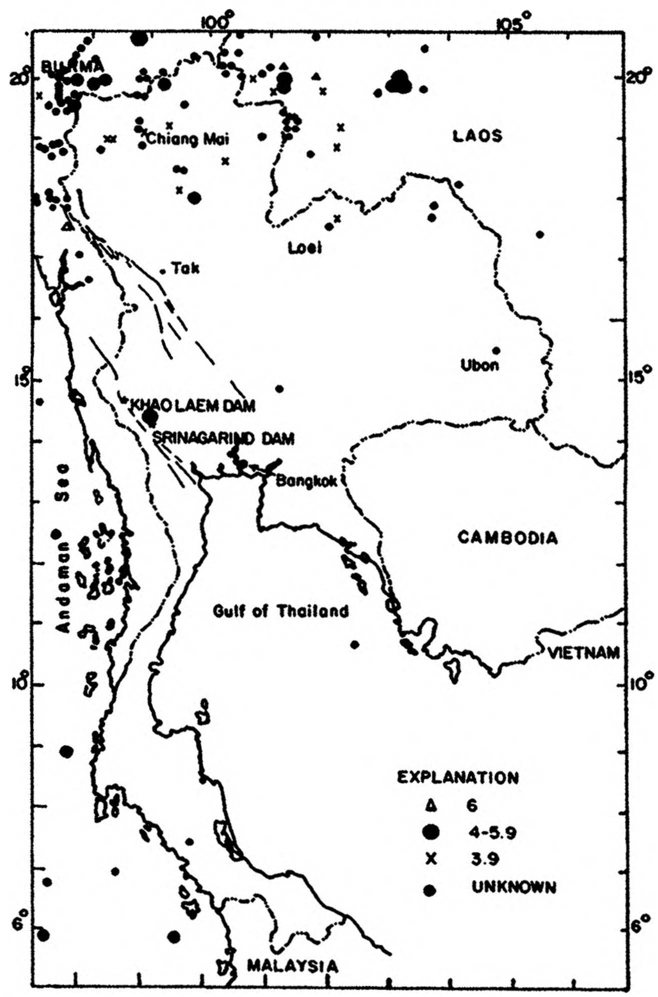


Figure 7 Earthquakes Occurring in Thailand 1900-1983 and The Couple Faults Manifestation

CONCLUSIONS

On the basis of geology, morphology, and tectonic history, Thailand can be subdivided into three major parts : 1) eastern Thailand, represented by the Khorat Plateau, 2) the depression of the gulf of Thailand and its extension northward as the central plain, and 3) the western and northern mountain belt that continues southward into the mountains of Malaysia. The gulf of Thailand, the central plain and the western mountain belt reflect the results of several major tectonics over the past few hundreds of millions of years. However, the latest tectonic activity in this region is believed to be the spreading in the Andaman Sea which is accommodated by the right lateral movement along major north-south trending strike-slip faults in Myanmar (Burma).

As a result of this tectonic activity, the Tertiary and younger deformation of western Thailand is characterized by north to northwest trending major fault zones. The most prominent of these zones are Tak and Three-Pagoda Fault with the lengths of several hundreds kilometers. Movement along these faults was related to left lateral displacement along the Shan Scarp and the Hninzee - Sagaing Faults to the northwest in Myanmar, (Burma) and appears to have continued until the late Cenozoic (Chantaramee, 1978). The nature of this couple faults is considered to affect the rock in this region in terms of dynamic metamorphism which created the high residual stress in the area. Srinagarind dam and reservoir is located in between these couple faults, as shown on Figure 7 therefore, the area is probably in a highly stressed condition. The strain accumulation has taken place and it might have reached its critical value before the reservoir filling. For these reasons the seismicity could be reflected from reservoir impoundment, and the release of the pre-existing strain energy could occurred through the local zone of weakness and caused the earthquake of April, 1983. With the evaluation of the overall characteristic seismicity based on the earthquake catalogs, focal mechanism solutions, earthquake relocation studies, air and ground geologic reconnaissance, analysis of remote sensing imagery and review of the pre-instrumental and instrumental seismicity of Thailand led to the conclusion as follows:

1. The Srinagarind reservoir is sufficiently large and deep to be considered a likely candidate for "Reservoir Triggered Seismicity" (RTS).

2. The 1983 earthquakes in the upper reaches of the Srinagarind reservoir occurred in an area that had no previous history of significant seismicity.

3. The focal mechanism solutions suggest the presence of a north-west trending causative structure which is coincided with the epicentral distribution and corresponds to the northwest trend of the old fault scarp along Quae Yai river and Huai Mae Phlu.

4. The east-west trending surface rupture is considered the fault plane rupture by the April 22, 1983 main shock, and is modeled as a reverse fault marking the southern end of the reactivated northwest feature.

5. The b-values for both foreshocks and aftershocks of the Srinagarind events are closely to unity. Moreover the foreshock b-value is greater than the aftershock b-value which is comparable to the RTS events.

6. The pattern of shock of the Srinagarind events is closely corresponded to Mogi's model type 2 which indicates the non uniform distribution of the external stress of the region.

7. After seven years of observation, it is clearly seen that the fluctuation and the load of the reservoir water had no direct effect on the earthquake occurrences.

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