SEISMIC SAFETY OF DAMS IN INDIA

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ABSTRACT

Filling of reservoirs has induced earthquakes in over hundred sites in the World including some fifteen cases in India. Such earthquakes have been damaging at a few places. Several geologic, geohydrologic, tectonic and seismic factors that influence the phenomenon of reservoir-triggered seismicity (RTS) are described. Certain seismic characteristics of the sequences of RTS which are found to differentiate such earthquakes from normal ones are mentioned. The factors of rate of filling identified to influence the level of seismicity are also described. These factors have been controlled in some cases of filling of dam reservoirs resulting into inhibition of likely induced seismicity. The phenomenon is mostly like triggering, hence, it has also been termed as Reservoir-triggered seismicity. The most important factor is that there has to be critically-stressed fault line within 10 km or at the most 15 km. However, the magnitude is found to exceed the expected level of the area by 10% or so. Seismic safety investigations are required to be carried out for all the proposed dams starting from the planning stage to have better idea of the local seismicity. The necessary investigations are outlined.

***Keywords** : India, Dams, Earthquakes, Reservoir Triggered Seismicity*

1. INTRODUCTION

Reservoir Triggered Seismicity (RTS) posed a challenge to the engineers for some years. Today, the phenomenon is reasonably understood as far as the dam safety is concerned (Gupta & Rastogi 1976, Packer et al. 1979, O'Reilly & Rastogi 1986, Gupta 1992). The paper gives a review of the phenomenon of Reservoir-Triggered Seismicity. Due to limited scope of this paper, only the salient points have been covered. A list of worldwide examples has been given. We have briefly discussed the discriminatory characteristic of RTS that discriminate such earthquakes from ordinary earthquakes, correlation of seismicity with water levels and mechanism of triggering of earthquakes.

2. WORLDWIDE CASES OF RTS

Total 167 cases (23% of large dams) of reservoir-triggered earthquakes are reported worldwide (Wilson et al. 2017). Majority of the sites where induced earthquakes of $M \geq 5$ occurred are in Stable Continental Regions of low to moderate seismicity. In some cases increase in seismicity after impounding is clear, while in others it is not outstanding. Damaging earthquakes exceeding magnitude 6 occurred at Hsingkengfiang (China), Kariba (Zambia), Kremasta (Greece) and Koyna (India, with largest M 6.3) in the sixties. The Koyna earthquake had registered an acceleration of 0.63 g in a gallery at mid height of the dam. So far only two dams Koyna and Hsinfengkiang have been structurally damaged. Damage has been in the form of cracks in monoliths. RTS was first noticed in 1932 for Oued Fodda dam in Algeria. Link between seismicity and variation of water level following the impoundment was identified by Carder (1945) for the Lake Mead reservoir in Colorado, USA. Seismic activity here began in 1938, three years after impounding 221 m high Boulder dam, with a reservoir volume of 36.7 km^3. An earthquake of magnitude 5 was followed by small shocks for some years.

There are five well-studied examples of RTS. First is Lake Kariba in Zambia where filling began in 1958 behind a 128-meter high dam. Although there is some evidence for minor earthquakes in the vicinity before the construction, until 1963, when the reservoir was full, more than 2,000 local shocks, mostly under the reservoir, were located with the use of nearby seismographs. The largest shock in September 1963 had a magnitude 5.8; the activity continued for over a decade.

Seismicity started soon after start of filling of 103m-high Koyna dam (with a 2.78 cub.km capacity reservoir). An earthquake of magnitude 6.3 triggered by this dam soon after impounding in 1967 claimed 200 lives, injured more than 1500 people, and destroyed 80 per cent of houses in the area; damage was also caused in populated suburbs up to 230 km away from the epicenter. Seismicity is continuing near Koyna for more than 4 decades. So far a total of about 1 lakh earthquakes of $M \geq 0.2$ have been recorded, out of which more than 150 earthquakes of $M \geq 4$ and 22 of $M \geq 5$ (Gupta et al. 2017).

A series of earthquakes that were quite conclusively reservoir-triggered occurred in China north of Canton. The Hsingfengkiang Dam (height 105 meters) was completed in 1959. Thereafter increasing numbers of local earthquakes were recorded, the grand total in 1972 amounting to more than 250,000. Of course, most were very small, but on March 19, 1962, a strong shock of magnitude 6.1 occurred. The energy released was enough to damage the concrete dam structure, which required partial dewatering and strengthening. Most earthquake foci were at depths of less than 10 kilometers near the deepest portion of the reservoir and some of the foci coincided with intersections of the main nearby faults. The fourth example is of 147m high Kremasta dam in Greece. Earthquakes here closely followed the filling and a damaging earthquake of magnitude 6.2 in 1966 followed 80m of rapid filling.

The fifth example is of Nurek dam with a height of 317 m built across River Vakhsh in Tadjikistan that is the second tallest dam in the World. Rogoun dam of height 355m built across River Vakhsh in Tadjikistan in 1996 is the tallest dam in the World. The Nurek dam had witnessed increased seismicity after impoundment. An earthquake of M 4.6 was triggered in 1972 that is immediately after the first stage of major filling. An earth-fill dam, it is constructed for irrigation and power generation of 3015 Megawatt (335 MW x 9).

3. RTS IN PENINSULAR INDIA

In Peninsular India there are about 100 dams of height over 50 meters. Eleven of these have evidenced some seismicity (Fig.1). In addition ten dams of smaller height have also witnessed seismicity. The dams where seismicity is most likely to have been triggered are Koyna, Warna (Talwani et al. 1996, Rastogi et al. 1997a, Rastogi 2017a), Bhatsa (Fig.2, Rastogi et al. 1986a, Rastogi 2017b), and Dhamni (Rastogi et al. 1997b). The possible cases are Idukki (Rastogi et al. 1989 & 1995), Sriramsagar (Rastogi et al. 1986b), Kelia and Jhuj (Chadha et al. 1999). In reservoirs like Makni (Rastogi 1994), Kinnersani, Parambikulam, Sharavathi, Ukai, Mula, Gandhisagar and Mahibajajsagar definite seismicity has followed impoundment but there are no clues to say that these were triggered earthquakes. In cases of other reservoirs like Ghirni, Mangalam, Sholayar, Nagarjunasagar and Srisailam incidences of isolated shocks have been reported (Guha et al., 1974; Rastogi, 1995) which may be part of regional seismicity. The sites of RTS are mostly in the west coast region that is moderately seismic. Narmada-Son zone is also similar where new reservoirs may show RTS. In Himalaya, reservoirs have not shown recognizable changes of seismicity. The reason for it may be that the variations in natural seismicity may be large and the changes introduced by reservoirs are not noticeable unless carefully observed.

Table 1 : Cases of earthquakes near dams in Peninsular India

SN	Dam	Height, m	Capacity, cub. km	Year of Impoundment	Year of Earthq.	Mag.
1	Idukki	169	2.000	1981	1978	3.5
2	Sholayar	105	1.527	1971	1971	2.0
3	Mangalam	29	0.255	1966	1975	3.0
4	Parambikulam	73	0.505	1967	1967	3.0
5	Sharavathi	38	-	-	-	2.0
6	*Koyna	103	2.780	1967	1967	6.3
7	Ghirni	16	-	1970	1970	2.0
8	Makni	10	0.214	1990	1993	6.1
9	Mula	47	0736	1972	1972	1.0
10	*Bhatsa	89	0.957	1989	1983	4.9
11	*Dhamni	59	0.285	1984	1994	3.8
12	Kelia	28	0.016	1983	1986	4.0
13	Ukai	81	8.511	1972	-	<3.0
14	Gandhisagar	52	7.323	1960	1982	3.0
15	Sriramsagar	43	3.200	1977	1984	3.2
16	Osmansagar	41	0.016	1920	1982	3.5
17	Kinnersani	38	-	1971	1969	5.3
18	Nagarjunasagar	125	11.560	1974	1979	3.6
19	Jhuj	48	0,022	1983	1986	4.6
20	Mahibajajsagar	68	2.059	1982	1994	3.0
21	*Warna	80	1.260	1998	1993	5.0

* Indicates well-studied case of reservoir-triggered seismicity. Kinnersani is nr. Bhadrachalam

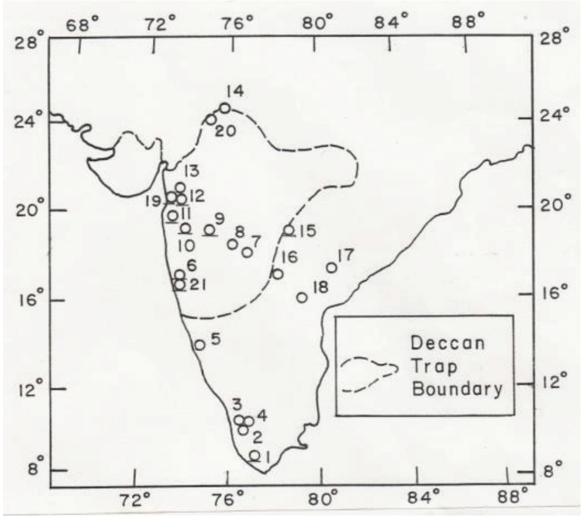

Fig. 1 : Locations of RTS cases in Peninsular India. Underlined reservoirs are likely cases of reservoir-triggered seismicity. The boundary of Deccan traps (volcanic basalts) in Western part is shown. 1.Idukki, 2.Sholayar, 3.Mangalam, 4.Parambikulam, 5.Sharavathi, 6.Koyna, 7.Ghirni, 8.Makni, 9.Mula, 10.Bhatsa, 11.Dhamni, 12.Kelia, 13.Ukai, 14.Gandhisagar, 15.Sriramsagar, 16.Osmansagar, 17.Kinnersani, 18.Nagarjunasagar, 19.Jhuj, 20.Mahibajajsagar and 21. Warna.

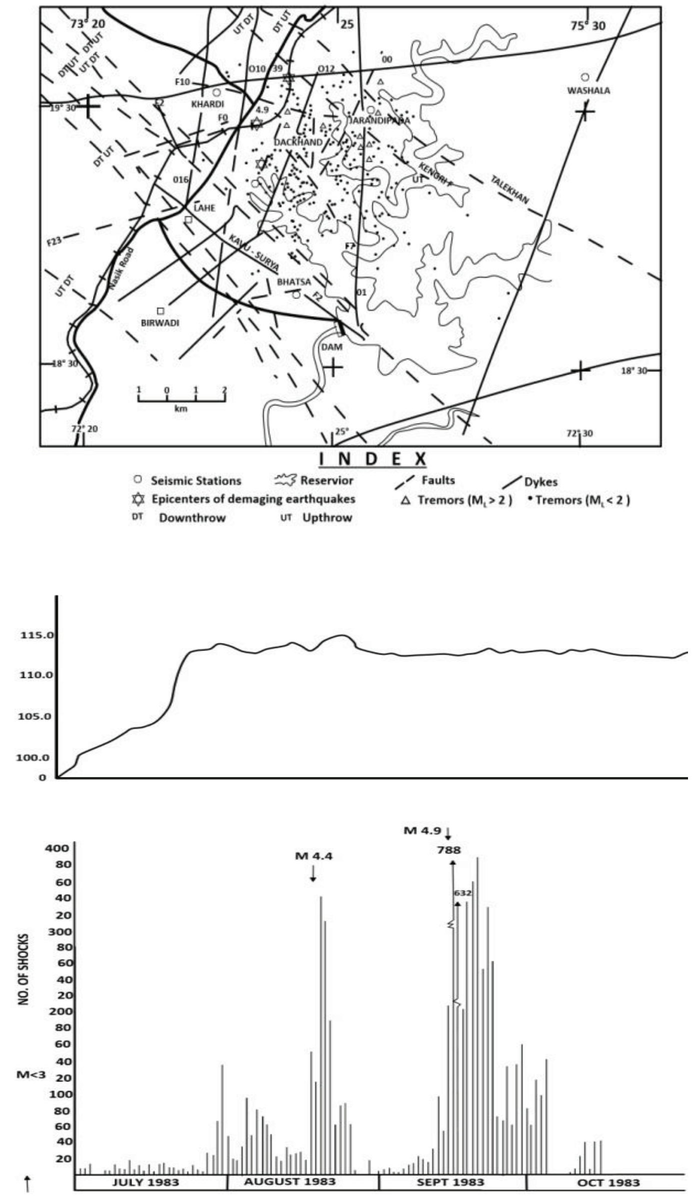

Fig. 2 : (left) Bhatsa reservoir boundary, local faults / lineaments and epicenters (right) seismicity started in the monsoon months when high water level had reached

4. MECHANISM OF RESERVOIR TRIGGERED SEISMICITY

Dead weight of water can cause readjustment of underlying substratum and small shocks near surface only. Every 10 m of water column causes 1 bar stress. Thus a 100 m deep reservoir would cause 10 bars (1 Mpa) stress. This incremental stresses may trigger earthquakes to about 10 km depth, if the ambient stresses are close to failure. The role of increased pore pressure produced by the reservoir loading is considered to be still more important. It spreads out as a pressure pulse into the crust. Its slow rate of spreading may take months or years to travel a distance of a few kilometers, depending on the permeability and amount of fracturing of the rock. If the pressure pulse finally reaches a zone of microcracks it might force water into them and decrease the normal stress that holds the strained faults, thus triggering the slippage.

Importance of the role of increased pore-pressure in earthquake generation came to light after triggering of earthquakes due to injection of waste fluid in deep wells in Denver, Colorado during 1962 - 1966 (Evans 1966). There were many seismic events: three of magnitude 5 to 5.2, and 1548 with magnitudes ranging from 1.5 to 4.4. In the Rangely oil fields, also in Colorado, USA (Raleigh et al. 1976) earthquakes with magnitudes up to 3.5 were triggered when the fluid pore-pressure was increased by 20 bars due to water injection for secondary recovery of oil during 1969 - 1973.

At some places peizometers were installed to measure the pore pressure changes vis-a vis reservoir levels. Since the formation of lake Kremasta the increased discharge in many springs evidenced the raised hydraulic potential (Snow 1972). The temperature of some of the springs decreased and the chemistry also got altered reflecting mixing of thermal and reservoir waters. Four peizometers installed near the reservoir recorded fluctuations similar to those of the lake levels. Effect of water level changes of the Bad Creek reservoir in South Carolina was faithfully transmitted to an observation well connected to it through a 250m long shear zone (Talwani et al. 1999). The well levels were 1/5th or more in amplitude as compared to the lake levels. Time of transmission was governed by hydraulic diffusivity. Starting 1995, 21 bore wells; 90-250m depth were drilled in the Deccan trap basalts in and around the seismically active region near Koyna and Warna reservoirs to monitor fluctuations of ground water levels. The pore pressure in the wells located in confined aquifer have shown correlation with lake level (Chadha et al. 2003).

Two categories of RTS have been noticed. In one category seismicity increases almost immediately after reservoir filling with swarms of small earthquakes, located at shallow depths in the immediate vicinity of or just below the reservoir. In the second category, there is a delayed response of some years after the reservoir has been filled. In this case the earthquakes tend to be larger, at greater depths and are at some distances (~ 10 km) from the reservoir. The first category of rapid response may be due to stresses caused by water load. The cases of second category of delayed response may be due to diffusion of pore pressure which is a slow process (Simpson 1976, Simpson et al. 1988).

Occurrence of earthquakes in the Indian Peninsula indicates that the region is stressed close to the failure. However, strain accumulation has to be at a slow rate in a Stable Continental Region away from both the spreading ridge in the Indian Ocean and the subducting boundary in Himalaya. Hence, RTS cases in critically stressed peninsular India belong to category one subjected to very rapid artificial stress loading cycle imposed on a very slow natural one.

5. COMMON CHARACTERISTICS OF RTS

Significant RTS is usually related to large dams of height over 100 m (and capacity > 1 km3) but RTS has also been observed at a number of relatively small dams of height 40 to 60 m. In two papers Gupta et al. (1972 a,b) identified the common features of RTS. These features are also helpful in discriminating RTS from normal earthquakes. Tremors are initiated and/or their frequency increased considerably following the lake filling. The earthquakes occur in the vicinity of the reservoir, mostly within 10 km from the from the reservoir. The factors influencing earthquake frequency and magnitude include the rate of increase of water level, duration of loading, maximum water level reached and the duration for which the high level is retained. For RTS sequences, the `b' values are high in the earthquake frequency-magnitude relations, and the ratio of the magnitude of the largest aftershock to the main shock (M1/Mo) is also high (~ 0.9). This is different for the normal earthquake sequences of the concerned regions that have low `b' value with high M1/Mo or high b value with a low M1/Mo. It is further observed that the foreshock-aftershock pattern of the RTS sequences corresponds with type II of Mogi's models (large no. of foreshocks), whereas the normal earthquake sequences of the corresponding regions belong to type I of Mogi's models (few foreshocks). The aftershock activity of RTS events decays very slowly compared to normal earthquake sequences. RTS sites are normally found to be located in the regions characterized by a volcanic past and the presence of fractured rocks, like Deccan Traps in western India.

Ruiz-Barajas et al. (2019) report over thousand shallow earthquakes of Mw 1 to 4.8 close to Pirrís Reservoir (Central Costa Rica) (total volume 3,6 * 107 m3, dam height 113m) soon after its filling in 2011. Mw 4.2 earthquake in December 2011 was 5 months after the maximum level. However, Mw 4.8 earthquake was in 2014 after a complete drawdown of water. Discriminatory characteristics like b-value and temporal pattern of shocks were detected.

Many reservoirs showed temporal association of maximum lake levels with episodes of high seismicity. It was noticed that the three episodes of high seismicity with one or more earthquakes of magnitude 5 or greater during 1967, 1973 and 1980 at Koyna (Talwani 2000) and two episodes during 1993-94 and 200 at Warna (Rastogi et al. 1997a) occurred within about 2 months after the water level in these reservoirs had exceeded the previous maximum. This behavior-the rocks displaying stress memory was observed at Kremasta (Snow 1972) and Nurek reservoirs and is similar to the

Kaiser effect observed in laboratory (Yoshikawa & Mogi 1981). Pande and Chadha (2003) estimated that water level changes cause propagation of pore pressure front and stress which is sufficient to trigger earthquakes at hypocentral depths of 6-8 km in Koyna.

6. GENERAL OBSERVATIONS ABOUT RTS

Earthquakes may occur along a number of faults. RTS is particularly noticed in low to moderate seismic areas. In highly seismic areas like Himalaya, the normal stress changes may be larger than the incremental changes caused by impounding, hence, triggered seismicity may only cause changes in the frequency pattern of the natural seismicity and change may not be discerned. Moreover, in thrust type of environment, triggering effect involves a greater amount of increase in pore pressure as compared to strike-slip or normal faulting environment. These may be the reasons that none of the large dozen reservoirs in Himalaya have shown any discernible change in seismicity (Gupta and Rajendran, 1986). Due to load effect alone there could be "seismic inhibition" in some such new reservoir areas, like at Anderson and Glen Canyon dams, USA, and Mangla and Tarbela dams, Pakistan.

Mostly RTS is noticed within a few years after impoundment, but has continued for long times. Strong earthquakes are continuing for over 5 decades at Koyna. Other examples are: Marathon, 8 years; Clark Hill, 22 years; Cajuru, 18 years; Aswan, 17 years. RTS was considered as a possible cause of M 7.1 earthquake, even after 44 years after impoundment of a small dam of 19 m height at Hebgen Lake, Montana, USA. Gandipet earthquake of M3.5 after 62 years of impounding the Osmansagar is a highly doubtful case of RTS (Rastogi et al. 1986c).

7. POSSIBLE CONTROL OF RTS

RTS may be inhibited by slower rates of impounding. Gupta (1983) pointed out that at Koyna, earthquakes of magnitude 5 or greater have occurred when rate of loading has exceeded 12 m/week. Similarly critical rates of loading were noted for several other reservoirs by Rastogi (1990,1995). He also suggested that impounding should be smooth (Fig.3). RTS is generally observed within a few years of impounding. Hence it was recommended that as far as possible the reservoir should not be exploited in the initial few years. Exploitation brings down the level and results in high rate of impounding subsequently. Another factor is that the reservoir level should not exceed the previous year's maximum level.

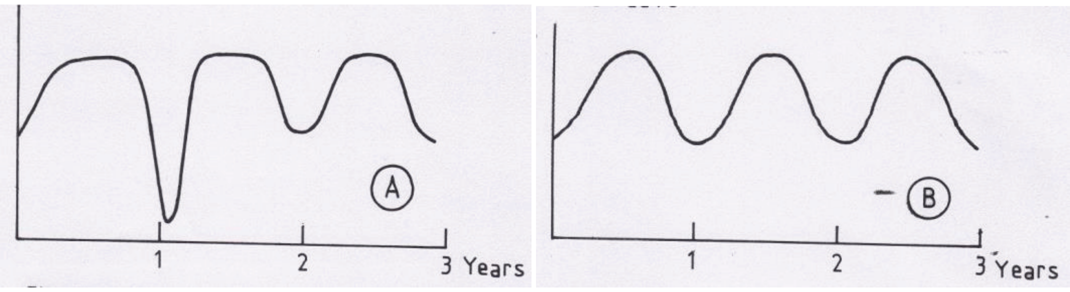

Fig. 3 : Abscissa indicates water level (A) Rapid filling may trigger seismicity near dams
(B) Recommended filling rate to inhibit earthquakes

8. HAZARDS TO DAMS DUE TO EARTHQUAKES

According to Guha et al. (1980) the main hazards to dams from earthquakes are due to surface faulting, strong ground movements, water waves in reservoir produced either by seismic waves or by landslides and rock falls and ground deformations associated with faulting. Ground deformations have been observed in a number of cases, e.g. the Baldwin Hills reservoir, Buena vista Hills, Kern County, USA In the case of earth and rock fill dams the damage occurs mainly through liquefaction failures. A number of dams were damaged by this during the Feb. 9, 1971 San Fernando earthquakes. Severe cracking and settlement developed in the upper and lower San Fernando dams. The cases of damage to other earth dams are Dry Canyon dam (1952) (Kern County earthquake), Sheffield dam (the earth-fill dam was totally damaged due to 1925 Santa Barbara earthquake), Hebgen dam (1959 Montana earthquake) and the Eklutna dam (1964 Great Alaska earthquake). Of these the Eklutna dam was very severely damaged and it had to be reconstructed. In 1963, the world's most tragic dam disaster occurred when an enormous rock mass fell in the reservoir created by Vajont Dam in Italy and the resulting overflow caused a huge wave which erased the town downstream and claimed about 2000 lives. The slippage of rock is thought to have been triggered by microearthquakes, which increased after reservoir filling in 1960.

A great tragedy was averted in the 1971 San Fernando earthquake just north of Los Angeles in southern California. The lower Van Norman Dam, less than 10 kilometers from the ruptured fault, had been built 30 years before by using the then common method of carrying soil for fill into position by water slicers. Subsequently, additional hydraulic fill had been placed on the dam. During the 1971 earthquake, a major earth slide took place in the interior portion of the dam, leaving only a meter or so of soil on the downstream side to stop the water flowing down onto a densely populated suburban area. Fortunately, the water in the reservoir was not at the allowable maximum at the time of the earthquake and the slim earth lip of the dam did not erode, and held the water in the reservoir until it could be drawn down. Meanwhile, 80,000 persons were evacuated from the downstream area.

9. NECESSARY INVESTIGATIONS

The necessary Pre-impoundment investigations for the study of reservoir-triggered seismicity include (i) Assessment of historical seismicity (ii) Monitoring of pre-impoundment seismicity a few years before impounding by at least one seismic station even if there is no seismicity while by five digital seismographs and one strong motion accelerograph covering the reservoir area if seismicity is expected (iii) Detailed geology/geophysics work for knowledge of faults/ fractures (iv) Geohydrological investigations should be carried out to determine the ground water conditions prior to impoundment (v) Installation of Geodetic stations to determine the geodetic changes due to reservoir impounding (vi) In-situ measurements by hydro-fracturing to determine the ambient stresses. Post-Impounding investigations, if seismicity is intense, include (i) repeat geohydrological and geodetic investigations (ii) Increase in number of seismograph and accelerograph stations, if required including the accelerographs on the dam body.

10. CONCLUSIONS

RTS is now accepted as a hazard for large dams. The dams in Peninsular India need to be designed for one magnitude unit higher than what is expected from seismic zoning map. The study of RTS has led to fundamental insight into the physical processes underlying the mechanism of natural earthquakes also. It has also provided important directions for research on earthquake prediction and control. Sites of RTS like Koyna are natural laboratories as the earthquake supply is assured in a known small zone, making them suitable for detailed earthquake physics and precursor related studies. Deep drilling achieved to 3 km depth in Koyna has provided new knowledge about the geology, faults and shear zones at depths of earthquakes.

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