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STUDY OF DAMAGES AND THROWS IN KOYNA EARTHQUAKE*

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Synopsis

The paper reports the observations of damages to structures during the Koyna earthquake. Most of the building structures in the area are single storeyed structures built in masonry. They are mostly in ruins. Study of cracks and failures of structures indicates several specific types which have been broadly analysed and presented. Likely seismic acceleration has been worked out in some cases. Direction-wise study of the throws of free objects has been made to draw inferences therefrom regarding the shaking during the earthquake. A scrutiny has been made to find out if the structural failures indicate any similarity by direction and if this one fits in with the throws of free objects. Figures have been given to indicate the observations made. Desirability of upgrading of seismic zones in the Deccan has been discussed. The necessity of educating the public in adopting the basic principles of earthquake resistant structures is emphasised as it is felt that any possibility of recurrance of earthquakes in the Peninsular region should be taken with alertness and caution rather than with panic. It is also necessary to take a nationwide review of materials to be used extensively for earthquake resistant construction.

Introduction

Since the Koyna Dam was brought in commission some tremors have been experienced in the Koyna region. But the tremors were of very shallow focus, say 4 km deep and of magnitudes upto 3.5. It is possible that such minor tremors might be due to some adjustment on account of sagging in the basin due to water load. But the heavy earthquake of 11th December 1967 must be having a deep-seated cause and cannot be attributed to the reservoir, though the tremors in the reservoir area might have triggerred the action at lower depth which was even otherwise in the being.

Heavily Damaged Area

Fig. 1. shows the heavily damaged area based on the observations of the author and a team of accompanying engineers which included Sarvashri M.N. Kulkarni, N.V. Joshi and Professrs. A.G. Patwardhan, Bapat and L.S. Sane. Damages to well-built structures in villeges were observed in particular and were taken as a measure rather than damages to poor type of construction or the rehabilitation activity. Buildings in many villeges which fetched useful information were the school building. the village panchayat office and a couple of houses and shops of leading merchants of the village. Damage to mud house of poor construction certainly aggravated the hardship of the villagers but such damage would not be a proper measure of the shock felt at the place.

Koynanagar experienced very heavy shocks. There was large concentration of buildings in Koynanagar. The township accomodated the offices of the Project in its subsequent stages and housed some 10,000 pessons. The earthquake took a toll of a hundred persons in Koynanagr and dishoused the entire population. Many of the structures were razed to the ground and others were badly damaged.

Surrounding villages which experienced heavy shock and damaged well-built structures include Helwak, Ghatmatha, Nechal, Goshtwadi (Gojegaon), Kamargaon, Nanel,

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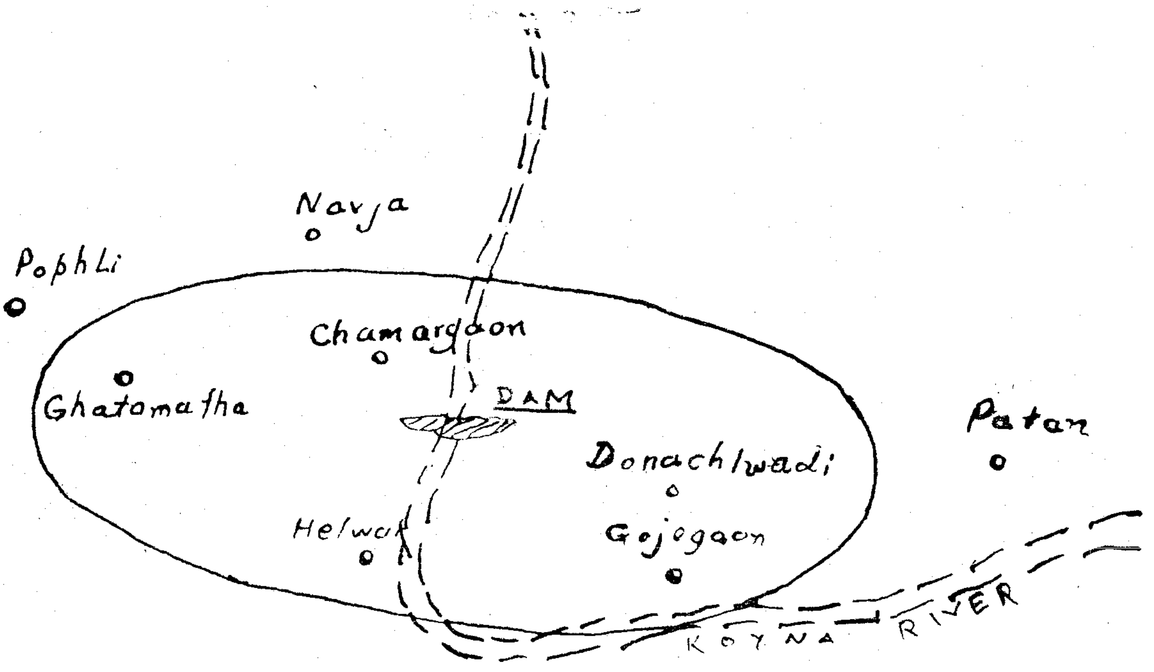


FIg. 1. Meizoseismic Area

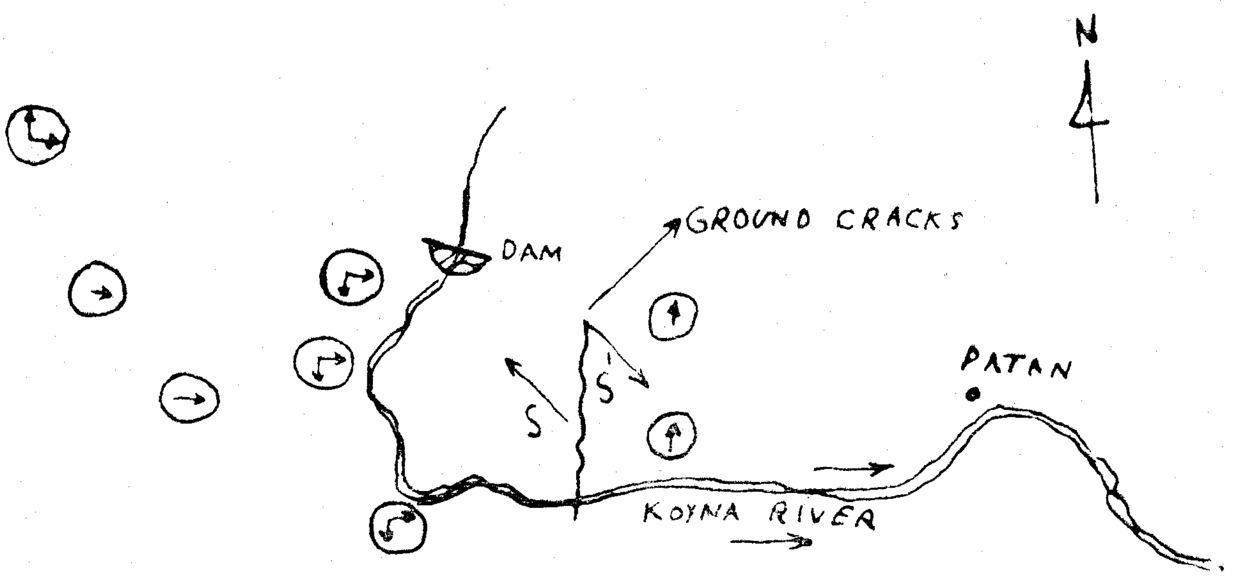


Fig. 2. Direction of Throws, Ground Cracks and Direction of Likely Tectonic Shear

Donachiwadi, Kadoli, Naneri, Lendori, and Morgiri. Navja only 4 miles upstream (north) of the Dam does not exhibit heavy damage to well-built structures. Heavy damage area extended to a distance of 6 to 8 miles east of the Dam and thus saved the Taluka capital of Patan. On the west Pophali, down the ghats, a distance of 6 miles as the crow flies has been considerably damaged though much less than Koynanagar. At Alore two miles further west well built buildings have cracked but the damage is much less.

Thus the zone of heavy damage looks to be an ellipse with major axis 20 km. in length mostly east-west and minor axis 6 km in length mostly north-south direction. Subsequent isosiesmals would be almost circular in shape touching Panchgani and Mahabaleshwar in the north. Nagthana and Karad in the east, and passing througn Sangmeshwar Taluka in the south and Chiplun Taluka on the west. Damages at Panchgani and Mahableshwar may be due to being situated on high peaks and further might have received more publicity than the damages at other less known places.

Ground Disturbance

It appears the ground disturbance is more exhibited along a more or less north south strip shown in Fig. 2 along Nanel and Donachi Wadi. This is confirmed by the observations of a team of Professors of Geology from Poona and Bombay.

Amongst the ground disturbances popularly reported are the heavy landslides and fall of heavy boulders in the area. The region being very hilly and consisting of steep mountain slopes, there is no wonder if large size landslides take place along the slopes. Such landslides might result in obstruction to roads and also involve loss of life and property. But they are not of much significance from the point of view of study of ground disturbance, for with a shock of such intensity landslides along steep slopes are inevitable.

Ground disturbances of significance are cracks across the slopes. Such cracks mostly running north-south are clearly exhibited across the hill slopes and across the Koyna river along the line indicated in Fig. 2. The ground disturbance has resulted in cracks across the road to Patan. There also appears a system of radial cracks on the road in the said region. This is indicated by a sketch in Fig. 3. The exact implication if any of radial pattern of cracks is not understood. Any way the observation in this respect is recorded here. The team of Geologists mentioned above have reported cracks in the ground in a width of 100 ft, the cracks being in a parallel system running N 15°W – S 15°E. The implication of the ground disturbance in relation to the direction is discussed later along with the throws of free objects.

There was no heavy concentration of structures in this area and there were no well built structures worth the mention. It appears this belt was shaken with a heavy intensity. The solitrary school building at Rammala Gojegaon (Gosthawadi) was a well built structure and has been razed to the ground with rubble from walls being thrown a distance of 7 to 8 ft.

Types of Damages to Buildings

Buildings in Koynanagar and Pophali are mostly ground floor structures founded on 'murum'. There are hardly any failures of foundations, this being in contrast with the observations the author had made during Anjar Earthquake (Cutch) of 1956. Buildings are in stone in cement morter for external walls and either stone or brick masonry for internal ones. Roof consists of asbestone cement sheets on timber trusses or masonry gables in case of interior walls and end walls.

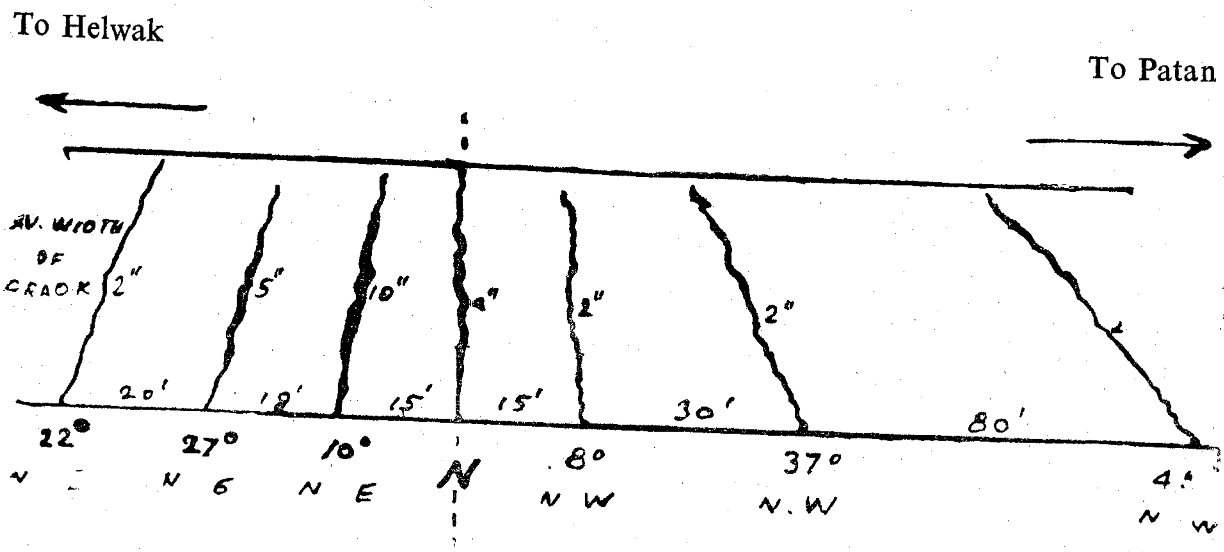


Fig. 3 : Radial Cracks on Guhagar Karad Road at Mile 55/1.

Stone masonry has been more heavily damaged than brick masonary. This may be due to the following reasons : (i) flat bedding afforded by brick masonry, (ii) less attraction of brick masonry to seismic forces because of lightness compared to stone masonry, (iii) stone masonry width of 15 inches adopted in building is often of poor workmanship. Places where timber pieces are embedded in stone masonry, as for instance purlins resting on masonry gables etc., are often weak spots where stones get loosened during shocks. It is likely that after a heavy shock timber frame work whose ends are embedded in masonry start vibrating with its natural period of vibration which is different than the natural period of the masonry wall. This sets up a differential motion between the two resulting in the loosening of stones in the masonry. The damage in such cases is due to the weakness of the joint between the timber piece and the masonry, but for which conjuction of materials of differing vibrational characteristics would have helped each other. A 15 inches wide rubble masonry wall is often weaker at the place where a timber member is embedded because rubble cannot easily be dressed to fitting shapes.

Damages to Trussed Roofs

The following practices in trussed roofs were noticed to produce failures during earthquake in the damages observed at Koyna-nagar aud Pophali.

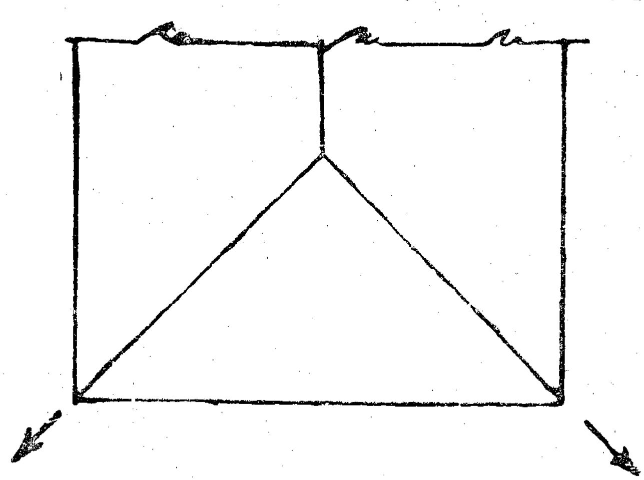


Fig. 4. Hip Rafters

(a) Hip rafters and valley rafters-Hip rafters resting on walls in an inclined position create horizontal thrust in the diagonal direction on the corner joint of two walls. Under seismic loads condition is worsened and hip rafters create a severe thrust on the corners under which the corners are very much prone to being thrown out (Fig. 4). Several cases of such failures were noticed. Valley rafters also create similar conditions.

(b) Collar beam trusses–Collar beam trusses are frequently used in buidings either to save cost or to increase the head room. In the absence of a regulr tie beam the principal rafter exert a push on the supporting walls. The situtation is worsened with horizontal seismic loads on the truss and the roof, with the result that the walls supporting the trusses are thrown out (Fig. 5).

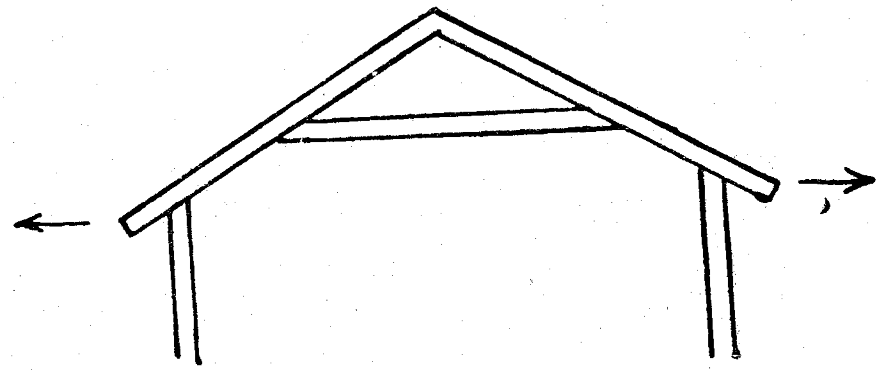


Fig. 5. Coller Beam Truss

(c) Knee braces or knee struts–Sometimes knee struts are provided to support the overhanging portion of the roof, all the more in rainy areas to protect from the weather. The struts are embedded in masonry at the lower end. While acting as a strut it causes a horizontal thrust on the wall. Under seismic loads the condition is worsened causing failure of masonry at the stem of the supports. The vibrations and the push on the roof are transferred to the strut which may either push the masonry at the root of the strut inside or pull it out. (Fig. 6). There are many failures of the latter type at Koynanagar.

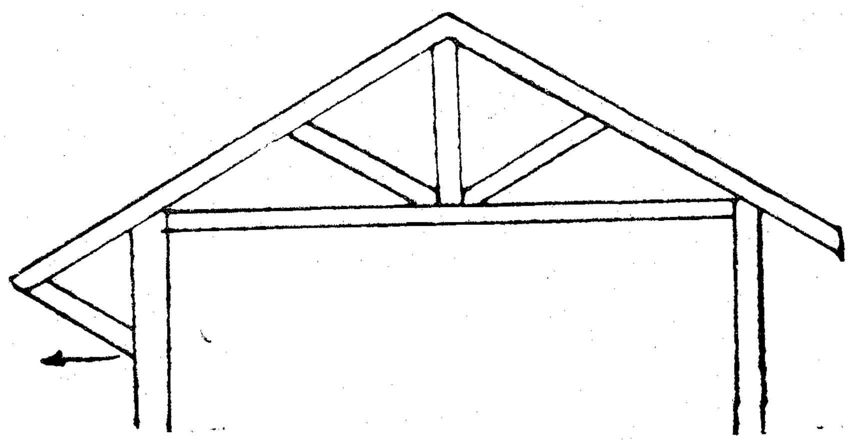


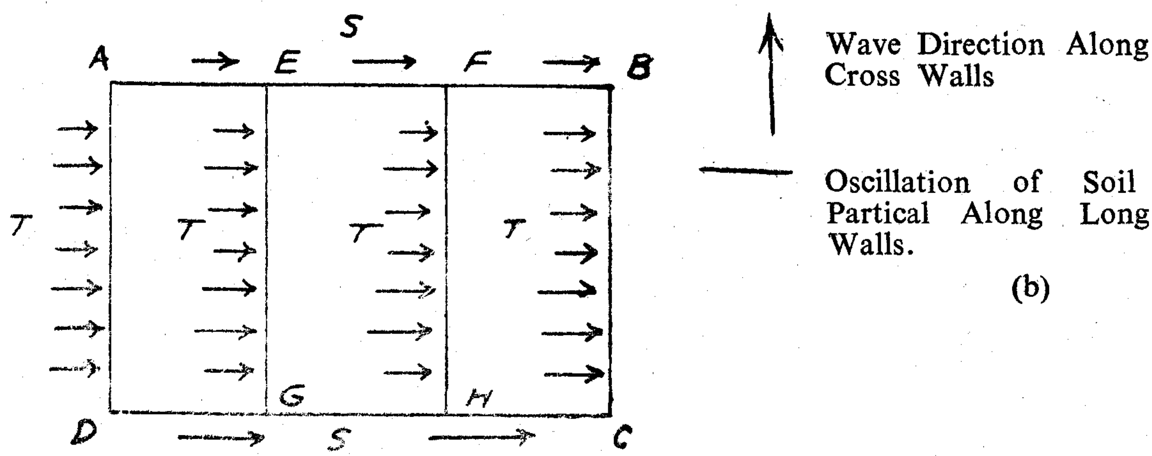
Fig. 6. Knee Brace

(d) Cracks are often observed extending from window corners upto purlins. Window corners are known to be weak spots wherefrom cracks orginate. Places where purlins are embeded in masonry gables are also weak spots as mentioned earlier. This explains the cracks extending from window corners to purlins.

Damages to Walls

Damages to buildings in earthquakes are due to the seismic waves. The actual displacement of a soil particle on the ground is quit complex, but is assumed as combination of different simple harmonic motions. The waves causing structural damage are transverse waves, so that the vibrating movement due to a particular simple harmonic motion is in a direction at right angles to the direction of propogation of the wave.

Considering the effect of a wave proceeding in the direction of the cross walls of a room, so that the ground particle describes simple harmonic motion in the direction of the long walls of the room, such wave shall produce shear forces on the long walls and side thrust on cross walls. (Fig. 7)

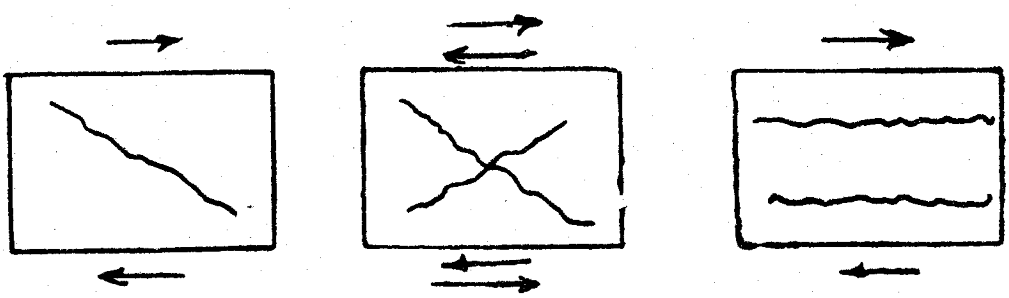


(a)

Fig. 7. Effect of Transverse Oscillation on Walls

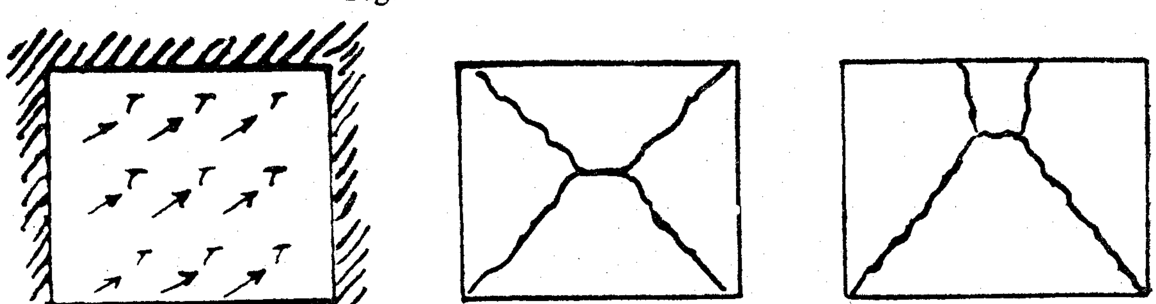
The oscillation causes reversible forces and can very well cause damage either in the direction of first oscillation or the reverse direction. But the force of the first oscillation is likely to be very predominent and that of subsequent oscillations rather subdued. All the same there is always a probability of the structure being weakened by the first oscillation and actually failling with the reverse oscillation.

Under the action of the forces as indicated the long walls would come under shear and should produce cracks of the pattern shown in Fig. 8.



(a) (b) (c)

Fig. 8. Crack of Walls in Shear



(a) (b) with adquate support on all sides (c) in case of no top support

Fig. 9. Crack Pattern of Walls with Side Thrust

Under the action of thrust forces T on cross walls shown in Fig. 7, the wall is loaded on its face with a more or less uniform load. With such loading, walls, AB, EG and FE in Fig. 7 will be subjected to a uniform loading, the walls being supported at their edges. The bottom will draw its support from the plinth beam, the top from the slab or roof to the extent such support is available, and on the sides the support will be afforded by long walls acting as butresses (Fig. 9).

With the direction of oscillation along long walls putting them in shear and putting the cross wall in side thrust acting as in Fig. 9A, the system produces a twist in the two corners. The junction of walls because of its partial rigidity transfers the twist to some extent to the long walls. This produces a clockwise rotation in one corner and an anticlockwise rotation in the other. Such rotation is observed at several corners. Sometimes an entire object is seen to have rotated. This is due to the formation of a couple of the seismic force on the object with some point acting as pivot. The direction of rotation merely depends upon which point acts as pivot. At times the motion can be combined one of rotation and translation.

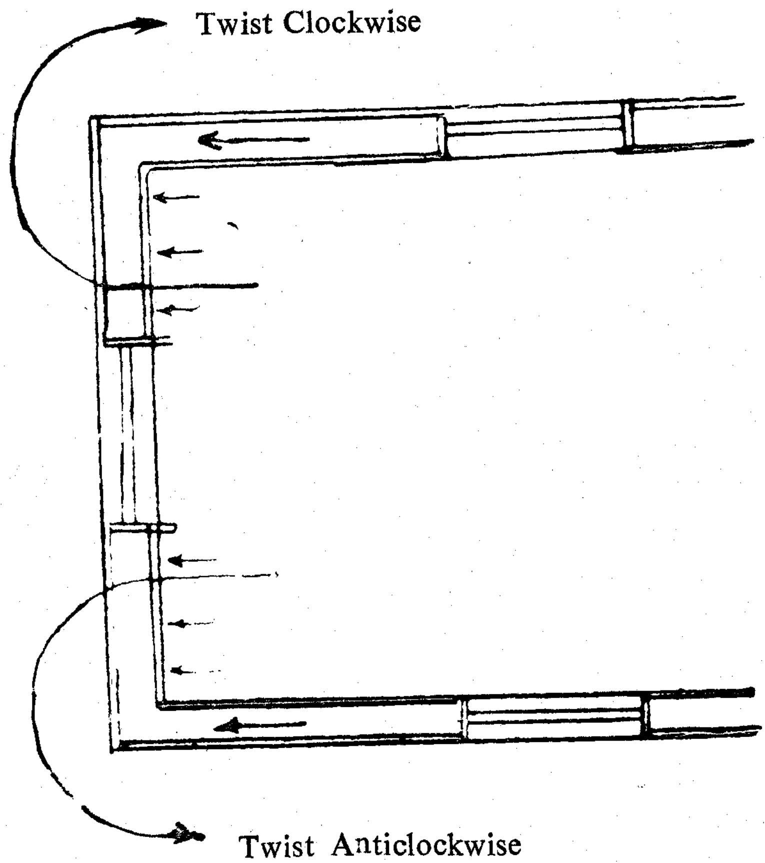
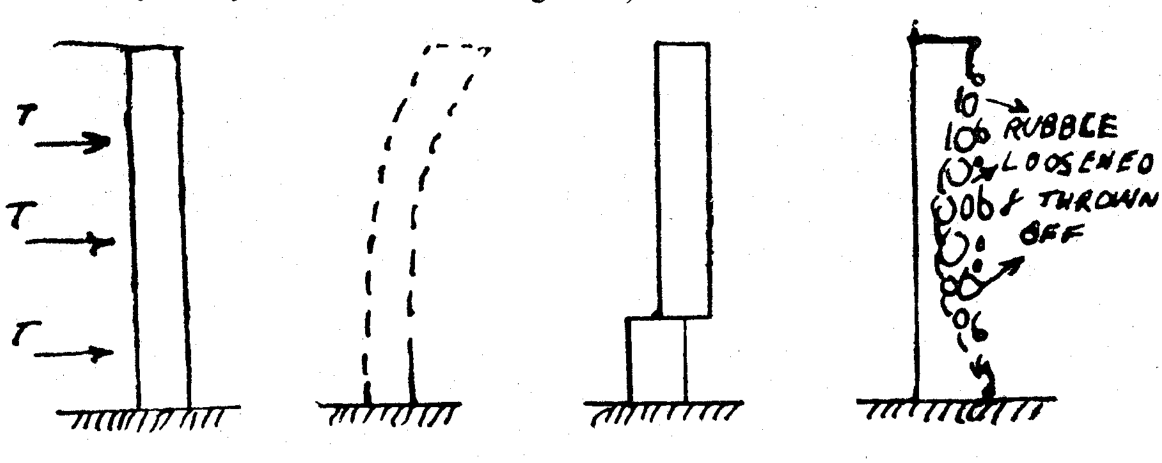


Fig. 9-A. Twisting of Corners

In the case of wall BC in Fig. 7, the side support would be from portions of long walls BF and CH, which come in tension. Under these conditions the cross walls may tear off from the long walls, may bend out in the vertical plane or may slide horizontally at any level as shown in Fig. 10 a, b and c.



(a) (b) (c) (d)

Fig. 10. Effect of Side Thrust on Fartnest External Wall

In the case of Fig. 10 c the upper portion of the wall has slided on the lower portion. There are some failures of this type.

In the case of Fig. 10 d the wall bulges out due to the side thrust T, which produces sagging in the wall with compressive stresses on the inner face of the masonry and tension on the outside face. The outside face may not be able to withstand the tension with the result that the stones would get loosened and fall down. At Koyna there are hundreds of failures of this type where stones on one face have fallen while stones on the other face standing intact. At first sight this is taken by many an onlooker as being due to bad workmanship, poor mortar and non use of bond stones. It appears that even with adequate bond stones, stones on the outside may still get loosened and fall down.

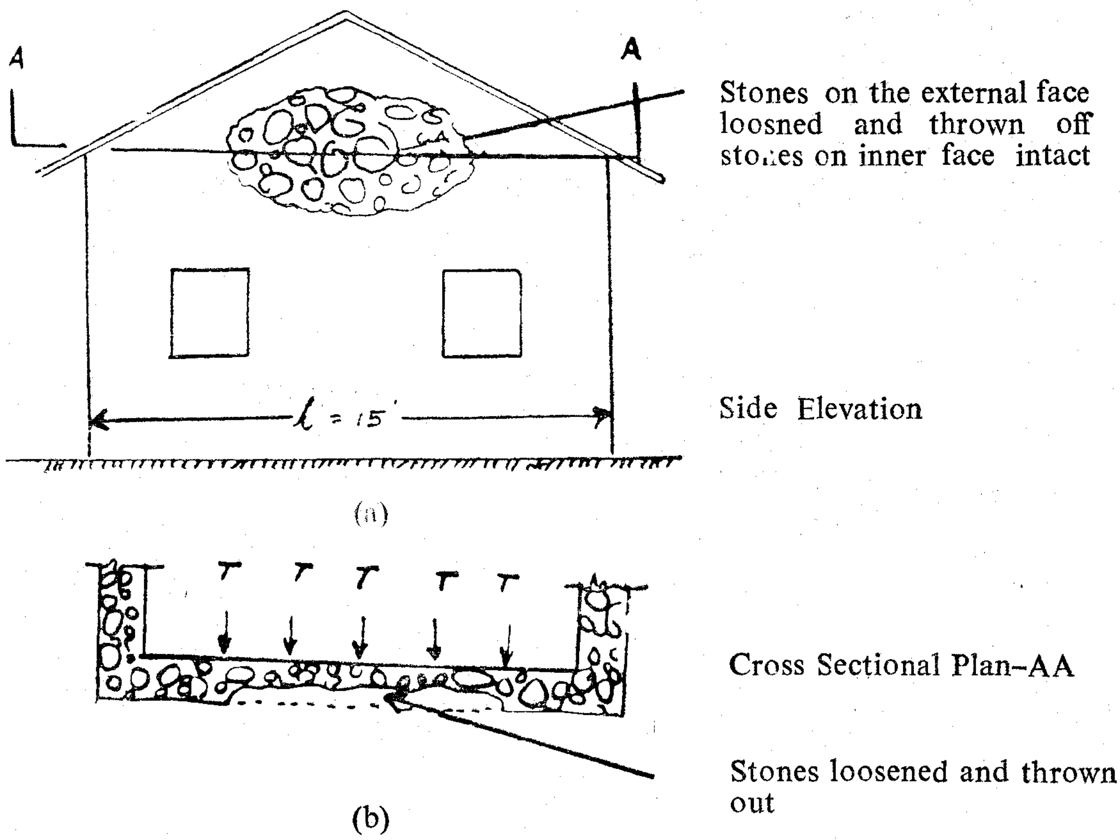


Fig. 11. Effect of Side Thrust on Gable wall

In several cases face stones in masonry gables have been thrown off (Fig. 11). At that level there is hardly any supporting reaction from the top or the bottom. The side thrust T $= \alpha$. W on the wall at that level produces bending moment with 1 as span. Let the effective seismic coefficient be equal to α, Seismic thrust per sft. $= \frac{1.25 \times 120}{2240} \cdot \alpha$ $= .067\, \alpha$ tons/sft.

Span $1 = 15'$

B.M. per foot width $= \frac{.067\, \alpha \times 15^2}{8} = 2\, \alpha$ ft. tons

Section modulus of the wall per foot widh $= 1/6 \times 1 \times 1.25^2 = 1/4$ ft^3.

Assume the crushing strength of masonry at 10 tons/sft and ultimate tensile strength at 1 ton/sft,

Bending stress produced in masonry $= 2\,a/\frac{1}{4} = 8\,a$ tons/sft.

When bending stress on tension side (i.e. the side with convex flexure) reaches 1 ton/sft., stones would be loosened and thrown off.

For such condition, $8\,a = 1$.

$$\therefore \quad a = \frac{1}{8} = 0.125$$

Under the assumptions made the fall of stones on the face of a wall indicates a horizontal seismic acceleration of 0.125 g.

In certain situations face stones on both the faces crumple and a big hole in the masonry is the result. Such ocurance is quite common.

It appears masonry walls fail more by side thrust than by shear as shear stress produced by the seismic force seldom exceeds the ultimate shear strength of masonry.

Damage to Dam Bridge on the Spillway and Control Room

There is not the least doubt that the dam must have shaken during the earthquake because of the very heavy intensity of the shock at dam site. It is very fortunate that the dam has been saved. Some relative movement seems to have taken place in the monoliths resulting in the increase of discharge of water in the galleries. Even the increased discharge is not a source of much worry, as it is not beyond tolerable limits. It appears some horizontal cracks have appeared on the upstream face of the dam at a depth of about 120 ft from top in the deep gorge region. This looks to be the neck section where from the downstream face becomes more steep upwards. As such it is likely to be a critical section. Moreover there may be a construction joint in the dam at that level. As the dam is a gravity dam its stability ordinarily is assured. The only matter of anxiety is the possibility of yet another shock recurring in the locality and then in that case the weakened dam being erquired to face a shock of similar or heavier intensity. From this point of view it looks advisable to strengthen the dam. This can be done by vertical prestressing by anchoring in the foundations on the lines done for Vaitarna Dam. It also looks desirable to provide vertical dowel pins to prevent sliding at the weakened horizontal plane.

The bridge on the spillway has suffered some damage. The concrete in the bearings to a depth of 6″ to 8″ has been crushed so as to expose the anchor bolts. The effect is more apparent at fixed bearings. The concrete of the main longitidunal beams resting on the bearings has also been damaged. This may be due to the impact on the bearing due to the vertical component of the seismic force.

The control room on the top of the dam has been damaged as its wall of cement concrete 12″ thick centrally reinforced has broken along the length and breadth of the room about 5′ from the floor. The crack appears at the construction joint. Even then it shows that the structure must have been severely shaken.

There appear to be some cracks in the body of the dam which look to be under close study. Though such cracks do not endanger the structure ordinarily, their appearance is a matter of some anxiety in view of the uncertainty of recurrence of shocks in the locality. It is gratifying that all efforts are being made to ensure the safety.

Throws of Free Objects

Throws of free objects often gives valuable information about the ground movement during the earthquake. This point was kept in mind during the field observations.

Movement of water storage tank of about 7500 gallon capacity situated on a hill near the A-type quarters fetches some useful information. The tank is 15′ in length 10′ in width and 10′ in height. It was supported on dwarf masonry plinth walls 4 nos. $\times 16' \times 1'-6''$, the height of plinth walls being about $1'-6''$ (Fig. 12).

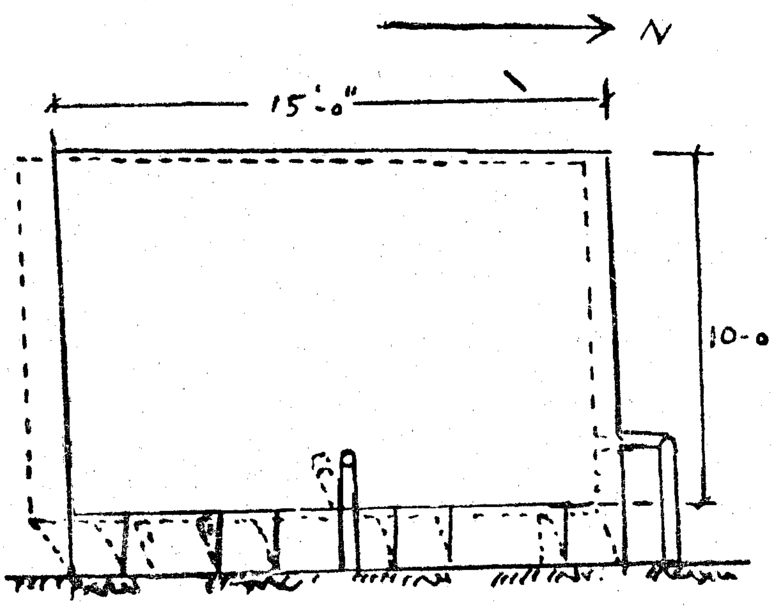


Fig. 12. Throw of Water Storage Tank

The plinth walls have been bent southwards opening up the northern portions and crushing the southern portions. The tank bottom remains attached to the southern wall but has slided on northern walls. A $2\frac{1}{2}''$ dia. G.I. pipe is connected to the tank from the front face, The pipe has been twisted during the movement. In a height of 2′, it has shifted 6″ along the S 40° W long face of the tank and 4″ along E 40° S at right angles to the face of the tank. The resultant shift of the tank is mostly due south.

Another pipe connection to the cross face shows a rotation in plan confirming the shift as above.

An estimate of the horizontal acceleration imparted to the tank during the shock is worked out as under :

Weight of water = 75,000 lb

Weight of water & tank = 80,000 lb

Horizontal acceleration = αg (due South)

Horizontal forces = 80,000 α lb = 35.7 α tons

Leverage of force on the top of masonry = 4′

Moment of horizontal seismic force on 4 masonry walls

$= 35.7\,\alpha \times 4 = 142.8\,\alpha$ ft. tons

Section modulus of 4 walls (width 1′–6″)

$4 \times 1/6 \times 10' \times 1.5^2 = 15\ ft^3.$

Since walls are slender in one direction they would fail in that direction due to the componant of seismic acceleration in that direction α g. cos 40° = .75 α g

Moment of effective horizontal seismic moment on 4 walls in slender direction

$= 142.8 \times .75\ \alpha$ ft. tons.

Bending stresses produced in masonry due to seismic moment

$$= \frac{142.8 \times 75\ \alpha}{15} = 7\ \alpha \text{ tons/sft.}$$

Compressive direct stress on masonry $= \frac{35.7 \text{ tons}}{4 \times 10 \times 1.5} = .6$ tons/sft.

Assuming the crushing strength of masonry at 10 tons/sft and ultimate tensile strength of 1 tone/sft.

The net tensile stress in masonry must have reached the value of 1 ton/sft.

$\therefore\ 7\alpha - .6 = 1$

$\therefore\ 7\alpha = 1.6\ ;\ \alpha = 0.23$

Thus on the presumption made, the least horizontal acceleration imparted to the tank during the shock must have been 0.23 g.

It may further be mentioned that some of the seismic force must have been spent up in twisting the two 2½″ G.I. pipe connections. But this factor would add to the minimum value of seismic acceleration estimated above.

It may further be noted that the actual ground acceleration during the earthquake is much more than the acceleration imparted to an object supported on the ground.

The net movement of the tank $= \sqrt{6^2 + 4^2} = 7.2''$ due south is indicative of the actual movement of soil particles on the surface of the ground. This inference is on the lines of the inference by Oldham regarding the movement of soil particles based on his classic study of tombs at Cherapunji in tne earthquake of 1897, in which case the movement was as much as 12″.

Study of movement of some more water tanks in Koynanagar shows movement in similar direction thought of a lesser extent.

Another study of interest was the southward sliding of a heap of testing concrete cylinders near the testing labotatory at the office building at Koynanagar. The heap consist of 14 layers, one above another resting in the interstitial concave gap between the cylinders. The cylinders were in two rows. The backward row is intact. The cylinders in the front row have slided forward (south) to the extent that the whole heap is on the point of toppling down. Here the concave gap between the lower row of cylinders forms a guide for the movement of the cylinders which can only take place either towards north or towards south. The movement is indicative of one component of the shock.

A definite southwards movement of falling objects was also noticed in Koynanagar as under :

(a) The southernmost stone slab of a tomb at Helwak bridge has been losened and has shifted southwards.

(b) The parapet stone slabs at the end of the railing of Helwak bridge, the central three spans of which have totally collapsed, shows a throw to the south.

An eastwards movement was also noticed in certain cases as under.

(c) A boundry stone buried in ground at Helwak was uprooted falling to the east.

(d) A 20′ long heavy steel rod for operation of gates of the Intake at Navja was hanging in the control room at the tower. It fell during the earthquake by shanking the supporting guides in the east-west direction. Whether the jerk was towards the west or the east cannot however be precisely inferred.

Directionwise Study of Throws and Failures

In Koynanagar throws of free objects shows a predominantly south componant as detailed above. Even as far as structures are concerned the southern ends and gables of large number of F and G type quarters oriented in the the east-west direction in front of Construction Power House have been more heavily damaged than the northern ends and gables. This is in conformity with the type of failure (Fig, 7) of wall BC with the initial direction of oscillation southwards and walls BF and CH not acting as effective buttresses. It must however be said that damages and failures of parts of structures do not yeild a firm evidence regarding direction of initial oscillations, in as much as the motion of ground particles is very complex in nature and that the possibility of a structure weakening during an oscillation and failing subsequently under the influence of another oscillation cannot be ruled out. The observation of damage being predominantly evident on the southern end walls of a large number of similarly placed structures is to be interpreted as broad generalisation. There are also shifts and damages towards east in certain cases.

Observations at Pophali at the foot of Western Ghats indicates damages to end walls and gables facing east in respect of similarly placed D and G type quarters. There also appears a large scale damage towards the north at Pophali. The situation of quarters at Pophali has to be borne in mind. The structures are mostly located on stepped ground sloping northwards joining the east-west valley of Vaitarni River. Pophali again is situated at the foot of Western Ghats at an altitude of 400′ wherefrom the ground slope is considerably reduced. Whether this situation is responsible for the direction of damage needs to be investigated.

The team of geologists from Poona and Bombay who surveyed a lot of damaged area find that the throws and damages is generally towards south in the area from Baja. Nanel and Donchi Wadi extending east (Fig. 2).

All these observations put together suggests that the tectonic shearing might have taken place in the NW–SE direction at about Donachi Wadi, with the seismic wave travelling SW therefrom with an initial oscillation of the ground in NW direction causing throws and failures in the southernly and easternly direction in the zone extending westwards, while the seismic wave might have travelled eastwards from Donachiwadi with the initial oscillation in the SE direction with the resulting throws and failures in the northernly and westernly directions (Fig. 2).

The system of shear might be in the direction NW to the west of tectonic disruption and SE to the east. Such system would induce diagonal tension in the east-west direction. It might also induce cracks in the ground in NS direction. A system of parallel cracks observed by the team of Geologists from Poona and Bombay appears somewhat in conformity with this direction.

Lessons for the Furture

The exact cause for heavy earthquake in the Deccan shield may be a matter of sharp controversy amongst the scientists. Coming to the practical aspect it looks advisable to accept the possibility of earthquake not only in Koyna region but also in Maharashtra as a whole and even the Deccan Peninsula as a fact of life, and upgrade the scismic zoning in the region. There is no reason for panic. Being a seismic zone does not put a bar on industrial or any progress of the region. It may only call for an alertness and watchfulness. People should be advised to bear in mind the basic principles of earthquake resistant design and construction. The structures should be light as far as possible so that they will not attract seismic forces and even if they do their is nothing much to fall to cause damage to life and property. As far as village houses are concerned the philosphy of such houses should be changed. Houses should be earthquake-proof houses rather than burgler-proof houses. As far as city houses are concerned a horizontal seismic force of about 5% is not likely to demand much strength of a structure than the application of wind load of say 10 lb/sft. to 20 lb/sft. Upgrading of zones will not burden the national economy to any considerable extent. If people are advised to adopt framed construction of whatever type either of bullies, timber, R.C.C. steel or prestressed-strength of such structures against any horizontal thrust moments is many times more than that of weight at bearing wall types, whereas increase in cost would be only nominial. Vibrational characteristics of such structures would be amply changed and structures would stand quakes much better. It would be very desirable to review the nation wide resources of suitable building materials which it would be advisable to use to enable earthquake resistant construction on an extensive scale. If that is done Koyna earthquake can prove to be a boon in disguise.