

Ground Rupturing Due to Entrapped Air/Gas in the Unconfined Zone

Manas Banerjee^{1*}, Vimla Prasad Singh¹, Hridaya Narain Singh¹,
Daya Shankar², Sunjay¹, Uma Shanker Singh¹

¹Department of Geophysics, Banaras Hindu University, Varanasi, India

²Department of Earthquake Engineering, University of Roorkee, Roorkee, India

E-mail: manasgp@yahoo.co.in

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Abstract

The sudden and large oscillation of pressure of compressed air/gas entrapped in porous medium due to the changes in the actual pore-fluid pressure, during recharge of water following intense rainfall after a prolonged period of dryness such that the rainfall intensity exceeding infiltration capacity, leads to the generation of hydro-tremors. These hydro-tremors cause ground rupturing, subsidence, developments of cracks in the building, etc. A theoretical model has been presented to estimate the successive values of compressed air/gas pressures due to the successive development of actual pore-fluid pressures and effective stresses during recharge of water of the unconfined zone during the onset of the summer monsoon of 2008 in the northern parts of India.

Keywords: Unconfined Zone, Compressed Air/Gas, Pore-Fluid Pressure, Hydro-Tremor, Ground Rupturing, Effective Stress

1. Introduction

The phenomenon of hydro-seismicity is caused by the changes in pore-fluid pressure during subsurface recharge of water following intense rainfall [1-6]. The recharge of water to a depth 2-6 km initiates hydro-seismicity caused by the hydrologic triggering of earthquake activity on critically stressed faults [3,7,8]; such tectonic earthquakes may be of magnitude $M_w > 3$.

The tremors which has magnitude $M_w < 3$ and confined within the unsaturated zone is referred to here as hydro tremors. The hydro-tremors have been explained by a mechanism that takes into account the entrapped air/gas in pore spaces of soil above water table which gets compressed maximum due to the actual pore-fluid pressure following heavy rainfall, and upon relaxation of pore-fluid pressure (due to the horizontal diffusion of near surface water), the pressure of the compressed air/gas oscillates, and this causes hydro-tremors to generate. The instant at which the air/gas expands suddenly due to the relaxation of compressive pore-fluid pressure, it develops effective stress [9] along the horizontal direction during its escape from the capillary channels through

the soil surface, which ruptures the ground surface.

It has been observed that the increased difference of energy of the compressed air/gas inside the soil produces noisy sound energy during its escape. The associated hydro-tremor generates elastic waves which shakes the ground. These are the observed facts. The incidences of ground rupturing have been found in areas, experiencing depleted amount of rainfall over the years associated with mining of subsurface water, and have been reported from many parts of the northern states of India in the initial phases of heavy rainfall during the onset of 2008 summer monsoon.

2. Materials and Method

2.1. Observation

The observed features of ground rupturing have been shown in **Figures 1(a-b)**. **Figures 1(a-b)** show the rupturing that occurred in the Kakori area of Lucknow district (on 17.06.2008) and in the Cantonment area of Varanasi district (on 25.06.2008) of Uttar Pradesh, India, respectively. The rupture dimensions were 0.1 to 0.5 m wide and 1 to 100 m long. During rupturing there was ejection of warm air/gas and water which was associated

*Corresponding Author

with shaking of ground. Also, a loud sound was heard during acoustic emission.

2.2. Analytical Model

It has been observed that after a prolonged period of dryness during summer season, the unsaturated soil is generally air/gas filled with the lowering of water table to a larger depth (Figure 2). The flow of water during recharge in such unconfined zone following a sudden heavy rainfall can be represented by the one-dimensional diffusion equation of the form:

$$\kappa \frac{\partial^2 \psi'}{\partial z^2} = \frac{\partial \psi'}{\partial t} \tag{1}$$



(a)



(b)

Figure 1. (a) The rupture on the surface occurred on 17.06. 2008 in Kakori area of Lucknow district of Uttar Pradesh, India; (b) The rupture of the surface occurred on 25.06.2008 in Cantonment area Varanasi district of Uttar Pradesh, India.

With the boundary conditions, such as:

- 1) $\psi' = \psi_0 \cos(2\pi t/T);$ at $z = 0;$
- and
- 2) $\psi' = 0$ at $z = \infty$

where ψ' is the pore-fluid pressure variation, ψ_0 is the amplitude, κ is the hydraulic diffusivity which is expressed as:

$$\kappa = \frac{K(\theta_{sat})}{S_s} \tag{2}$$

And is assumed constant ($\kappa = 0.30256 \text{ m}^2/\text{s}$). $K(\theta_{sat})$ is the saturated hydraulic conductivity for saturated water content (θ_{sat}), and S_s is the specific storage of the saturated layer.

The solution of equation is written as:

$$\psi' = \psi_0 e^{-z\sqrt{\pi/T\kappa}} \cdot \cos\left(\frac{2\pi t}{T} - z\sqrt{\pi/T\kappa}\right) \tag{3}$$

When there occurs intense rainfall for sometimes after a prolonged period of dryness, a constant height of water (a) stands at the ground surface (Figure 3). The unsaturated soil profile starts getting recharged, and the moving wet-front goes on compressing the filled air/gas of the soil above the water table (Figure 3). The hydrostatic pressure thus developed due to recharge of water can be expressed as:

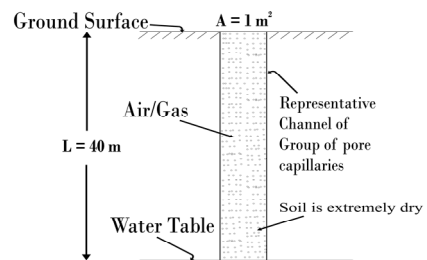


Figure 2. The unsaturated soil column is filled with air/gas before recharge above the water table. The depth of water table (L) is 40 m.

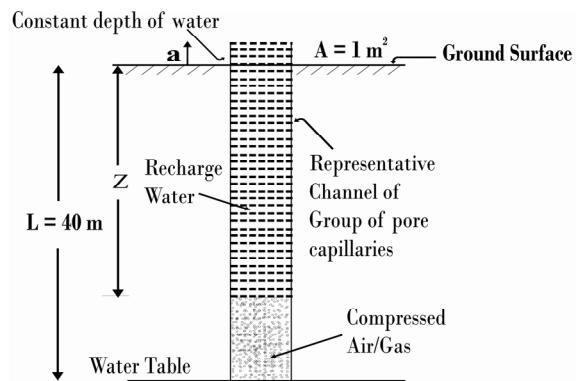


Figure 3. The compression of filled air/gas due to the recharge of soil under the constant height of standing water (a) at the ground surface following intense rainfall.

$$\psi_h = \rho_w g z + g \alpha \cdot \rho_{ag} (L - z) \quad (4)$$

where: ψ_h is the hydrostatic pressure; L is the depth to the water table; z is the depth to which the wet-front has moved; $\alpha = (L/(L - z))^2$, a factor by which the density (ρ_{ag}) increases due to compression; ρ_w and ρ_{ag} are the densities of water and air/gas, respectively; and g is the acceleration due to the gravity.

The development of actual pore-fluid pressure (ψ_f) after a substantial amount of time can be expressed as:

$$\psi_f = \psi_h + \psi' \quad (5)$$

After dividing ψ_f by ψ_0 , we can write the normal value of the actual pore-fluid pressure as:

$$\psi_n = \frac{\psi_f}{\psi_0} \quad (6)$$

where: $\psi_0 = 1.01325 \times 10^5$ pa. When the recharge water moves downward towards water table, it goes on compressing the air/gas till the pressure of the air/gas (ψ_{ag}) is balanced against the actual pore-fluid pressure (ψ_f), such that $\psi_{ag} = \psi_f$. Now, the normal value of the actual pressure of the air/gas can also be written as:

$$\psi_n = \frac{\psi_{ag}}{\psi_0} = \frac{\psi_f}{\psi_0} \quad (7)$$

When rainfall ceases, the percolation and the horizontal diffusion of water occurs this causes relaxation in the hydrostatic pressure (Figure 4). The relaxation process leads to the oscillation of the level of water, and ultimately level falls. And, the relaxed pore-fluid pressure ψ_{rf} can be written as

$$\psi_{rf} = \psi_h + \psi' - \psi_{rh} \quad (8)$$

where:

$$\psi_{rh} = gl(\rho_w - \rho_{ag}) \quad (9)$$

In Equation (9), l is the depth to which water level falls during relaxation in pore-fluid pressure. Now, if we divide ψ_{rf} by ψ_0 and call it the normal relaxed pore-fluid pressure ψ'_n which can be expressed as:

$$\psi'_n = \frac{\psi_{rf}}{\psi_0} \quad (10)$$

When the magnitude of ψ_{rh} is negligible, $\psi_n - \psi'_n = 0$; and when the magnitude of relaxation (ψ_{rh}) in actual pore-fluid pressure is large, $\psi_n - \psi'_n > 0$, the compressed air/gas expands and causes the rupture on the ground surface according to a Mohr-Coulomb criterion.

In terms of effective stress, we state that the actual pore-fluid pressure ψ_f is equivalent to the effective stress σ'_{ij} in the Bishop's stress equation (Equation (10)

of [9]). We can write their equation (for 1D problem by taking $\chi = 1$ for saturation) and dropping kronecker delta as

$$\sigma'_i = \sigma_i - u_w \quad (11)$$

where: σ_i is the total stress (due to the hydrostatic pressure) and u_w is the pore water pressure. Now, the Equation (11) can be written for the total vertical (σ'_v) and the total horizontal (σ'_h) stresses as:

$$\sigma'_v = \gamma z - u_w \quad (12)$$

And

$$\sigma'_h = K_o \cdot \gamma z - u_w \quad (13)$$

where: K_o is the lateral earth coefficient (σ'_h/σ'_v), which is constant at rest.

2.2.1. Effective Stress during Sudden Heavy Rainfall

As we have considered in the present treatment that when an unsaturated soil becomes saturated due to sudden heavy rainfall, the effective vertical stress is due to ψ_{ag} ($= \psi_f$) and can be written as:

$$\sigma'_v = \psi_h + \psi' \quad (14)$$

And the effective horizontal stress can be expressed as:

$$\sigma'_h = K_o \cdot \psi_h + \psi' \quad (15)$$

where: ψ' and ψ_h are given by Equation (3) and Equation (4), respectively.

At balanced stress state, when $\psi_n = \psi'_n$, the normal stress is given as:

$$\sigma = \frac{\sigma'_v + \sigma'_h}{2} + \frac{\sigma'_v - \sigma'_h}{2} \cos 2\theta \quad (16)$$

And the shear stress is given as:

$$\tau = \frac{\sigma'_v - \sigma'_h}{2} \sin 2\theta \quad (17)$$

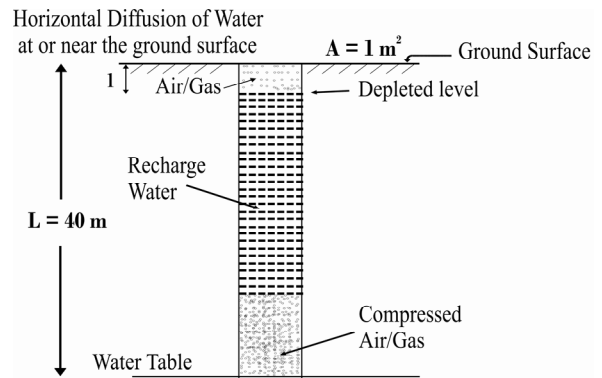


Figure 4. The percolation and horizontal diffusion of water occurs after the cessation of rainfall with the depletion of water level.

2.2.2. Effective Stress upon Cessation of Rainfall

As stated earlier that when rainfall ceases, there occurs relaxation in pore-fluid pressure and thus affecting the effective stress. In this situation, the effective vertical stress may be written by combining Equation (8) and Equation (14) as:

$$\sigma'_{vr} = \sigma'_v - \psi_{rh} \tag{18}$$

Similarly the effective horizontal stress is written by combining Equation (8) with Equation (15) as:

$$\sigma'_{hr} = \sigma'_h - K_o \psi_{rh} \tag{19}$$

where: σ'_{vr} and σ'_{hr} are the effective vertical and effective horizontal stresses during relaxation in pore-fluid pressure.

At relaxed stress state, when $\psi_n - \psi'_n > 0$, the normal stress is expressed as:

$$\sigma_r = \frac{\sigma'_{vr} + \sigma'_{hr}}{2} + \frac{\sigma'_{vr} - \sigma'_{hr}}{2} \cos 2\theta \tag{20}$$

And the shear stress is given as:

$$\tau_r = \frac{\sigma'_{vr} - \sigma'_{hr}}{2} \sin 2\theta \tag{21}$$

3. Discussion

The annual cycle of pore-fluid pressure, ψ' can be estimated by Equation (3) for $z = 0$ (the top boundary condition). The normal pore-fluid pressure (ψ'/ψ_0) variation is shown in **Figure 5** (for the period Jan - Dec). In this condition the soil is extremely dry with an increased depth of water table in the unsaturated zone. The strength of the soil can be represented by the stress field (τ_s) as:

$$\tau_s = \tau_0 + \sigma.c_f \tag{22}$$

where: τ_0 is the cohesive stress binding the soil particles together; σ is the normal stress; and c_f is the frictional coefficient [10].

A soil being a poro-elastic medium, it holds water in its pore spaces under saturation. And, intermittent filling and draining of saturated water of soils are governed by the phenomena called sorption and de-sorption under condition of flux and no-flux of water, respectively, through the soil surface. The extreme conditions of sorption and de-sorption in nature occur during the rainy season and summer season, respectively. It has been observed that there occur ruptures on ground surface following recharge of soil under the condition of constant depth of water standing at the surface due to heavy rainfall during the initial phase of summer monsoon (in the northern parts of India). The dimension (length x width) of such surface ruptures are found to be in the range from (1 m × 0.01 m) to (100 m × 0.50 m).

To explain such phenomenon of ground rupturing in the initial phases of intense summer monsoon rainfall, the model estimates the successive values of the compressed air/gas pressures due to the successive development of actual pore fluid pressures during the recharge of water in the group of capillaries forming channels with the constant height of water (a) at the surface of the unsaturated soil. As recharge of water continues (**Figure 3**), the compression of air/gas increases with the increase of the hydrostatic pressure. The successive values of the build up pressure are shown in **Figure 6** for recharge of water up to a depth of z when the downward movement of recharge water ceases. The curve X corresponds to the pressure of the compressed air/gas which is balanced against the actual pore-fluid pressure ($\psi_n = \psi'_n$, for $\psi_{rh} = 0$) that developed during the wet-front movement to a depth of z , not allowing the air/gas to escape from the pores (Equation (7)). Here, according to Equation (7), ψ_n is the normalized pressure of air/gas now and ψ'_n is the normalized pressure of the pore-fluid during relaxation ($\psi_{rh} \neq 0$). The movement of water ceases when

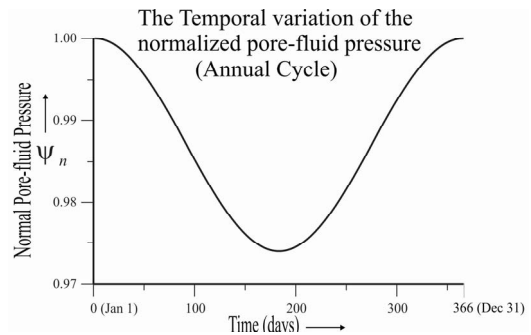


Figure 5. The annual cycle of the normal porefluid pressure versus time at the ground surface.

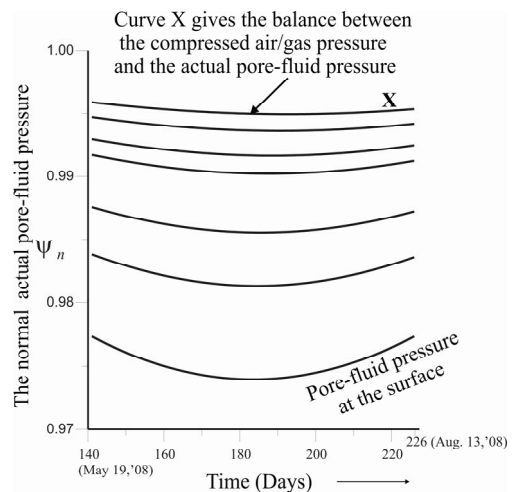


Figure 6. The variation of the normal actual porefluid pressure (ψ_n) of the entrapped compressed air/gas with time.

the entrapped air/gas cannot be compressed further, a critical stage is reached (*i.e.*, when the condition $\psi_n - \psi'_n > 0$ is about to occur and any decrease in the normal stress and increase in shear stress together with decrease in shear strength will lead to rupture of the soil). This occurs when the differential horizontal diffusion of water of the surface and near surface pore spaces takes place (**Figure 4**). The resulting hydrostatic pressure starts fluctuating which leads the compressed air/gas to oscillate till the percolation and the differential horizontal diffusion continues. When the magnitude of relaxation in actual pore-fluid pressure is sufficiently large ($\psi_{rh} > 0$), ψ'_n reduces. A plot of the normalized relaxed pore-fluid pressure variation with time has been shown in **Figure 7**. For a situation when the balance between the relaxed hydrostatic pressure and the compressed air/gas pressure breaks down, the condition $\psi_n - \psi'_n > 0$ occurs, and the entrapped air/gas expands suddenly which generates compressional waves at the surface. The rupturing can be explained in terms of the stress law using the effective vertical (σ'_v & σ'_{vr}) and horizontal (σ'_h & σ'_{hr}) stresses, the normal stress (σ), and the actual shear stresses (τ & τ_r); where the shear stress (τ) and the shear stress (τ_r) are associated with balanced stress state and relaxed stress state, respectively. When $\tau_r > \tau$, the rupture occurs as the effective strength of the soil reduces that can be expressed as:

$$\tau_s = \tau_0 + c_f \cdot (\sigma - \psi_{ag}) \tag{23}$$

By combining the Equations (16), (17) and (22), we obtain:

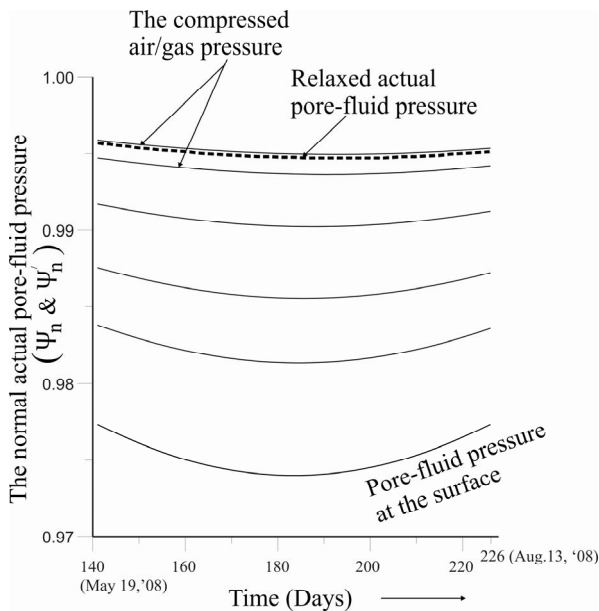


Figure 7. The normal pore-fluid pressure variation with time after the cessation of rainfall.

$$\tau = \tau_s - \tau_o - c_f \cdot \frac{\sigma'_v + \sigma'_h}{2} \tag{24}$$

Now combining the Equation (22) with Equations (18), (19), (20) and (21), we get

$$\tau_r = \tau_s - \tau_o - c_f \cdot \left[\frac{\sigma'_v + \sigma'_h}{2} - \psi_{rh} (1 + K_o) \right] \tag{25}$$

Or,

$$\tau_r = \tau + \psi_{rh} \cdot (1 + K_o) \tag{26}$$

The actual shear stress (τ_r) is now greater than the shear stress (τ). Therefore, during the process of escape of expanding air/gas from the pore-channels of group of capillaries through the ground surface (**Figure 8**), there would be an increase in shear stress (Equation 26) and decrease in normal stress σ_r (Equation 20) which leads to the failure because of reduced strength of the soil (Equation (23)). The failure according to the Mohr-Coulomb criterion is depicted in **Figure 9**. In **Figure 9**, the normal stress (Equation (16)) for σ'_v and σ'_h has been shown in Mohr circle 1 and the shear stress is τ . Since the relaxation in actual pore-fluid pressure is by an amount ψ_{rh} which causes the effective vertical stress and the effective horizontal stress to decrease to σ'_{vr} and σ'_{hr} , respectively. Now the normal stress σ_r (Equation (20)) for σ'_{vr} and σ'_{hr} has been shown in Mohr circle 2 which moves the circle closer to the Mohr-Coulomb failure criterion line and now the shear stress is τ_r ; and as $\tau_r > \tau$, the rupture occurs. The rupture offset at the ground surface has been shown in **Figure 10**. The two

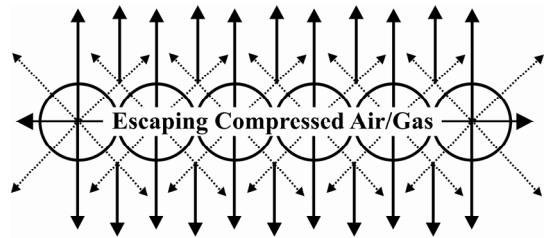


Figure 8. The escape of expanding air/gas from the pore channels of group of capillaries through the ground surface.

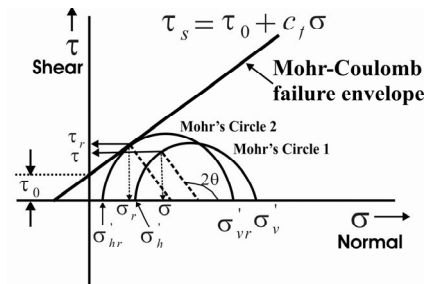


Figure 9. The relationship between the normal and shear stresses and the Mohr-Coulomb failure envelope.

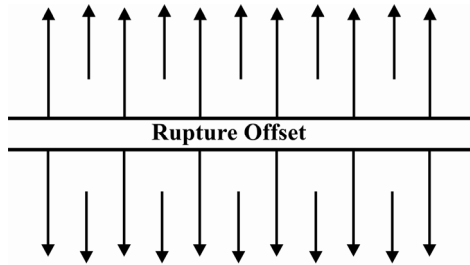


Figure 10. The rupture offset due to the rupturing of ground surface.

figures (Figure 8 and Figure 10) also depict the resultant force vectors due to the escaping compressed air/gas which are perpendicular to the rupture offset boundaries. The rupture offset is proportional to the magnitude of the energy (E) released which is generally of the order of 10^7 J to $10^{7.2}$ J. (The energy is calculated using the formula: $E = \rho_w g h^2 A$; where $\rho_w = 1000 \text{ kg/m}^3$, $g = 9.8 \text{ m/s}^2$, $h = 40 \text{ m}$ and $A = 100 \text{ m}^2$). This is equivalent of energy magnitude ($M_w = 1.2$ to 1.3). The energy magnitude is calculated as $M_w = (\log E - 5.24) / 1.44$. It has been observed that this process is associated with ejection of warm air/gas and water, and sometimes, with subsidence at places. And, during rupturing there generates the hydro-tremors.

4. Conclusion

The mechanism of the proposed model could explain the incidence of ground rupturing in the areas experiencing depleted amount of rainfall over the years associated with mining of subsurface water, and have been reported from many parts of the northern states of India in the initial phases of heavy rainfall during the onset of 2008 summer monsoon.

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6. References

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