Predicting the safety factor of ash impoundment against liquefaction

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Abstract. Fly ash exhibits poor strength properties and is susceptible to liquefaction when subject to dynamic loading. Coal power plants produce abundant of fly ash and increasing each year. With limited area to dump the ashes, those facilities will raise the embankment which resulted in higher risk of failure due to liquefaction during earthquake. Calculating the factor of safety using cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) are relatively easy, on the other hand, gathering information for CRR depend on laboratory testing or onsite testing which difficult to get the sample, time consuming and expensive. This study shows example of using equation from previous research to predict the CRR by using only CSR value.

1. Introduction
Suralaya power plant is one of the biggest power plants in Indonesia, produces fly ash or also known as “abu terbang”, as a waste from burning coal. Fly ash produced from this plant is in high demand for concrete batching plants as an admixture for their concrete mixture that will be used for construction. Although we have option for ordering concrete mixtures without fly ash but some people prefer to order concrete with fly ash cause lower in price. There are debates for using fly ash as an admixture in concrete mixture but in this paper the argument will be neglected and focus on fly ash itself. Bottom ash and fly ash are produced at rates of 12-20% by weight of the original coal (Chen et al., 1991).

Fly ash is generally considered to be an industrial waste; the flue gas carries fly ash as residue of the burnt coal, which is collected using electrostatic precipitators (ESP). Garlisch (2010) stated that fly ash is the ash that rises up and is trapped by the stack filters. In United States Right et al. (1998) reported that only 20% of the ash by-products are recycled while 80% are landfilled at the power plant site.

According to Indonesiapower.co.id, electricity generation on Java and Bali grid is dominated with coal power generation plants. Indonesia Power (IP) is manages coal power plants in Suralaya, Lontar, Labuhan, Pelabuhan ratu, and Adipala

The biggest coal suppliers for power plants under IP are Bukit Asam, Adaro, Berau Coal and Kideco with indicative ash content is about 2 – 4 %. Until now, IP already cooperates with cement industries and brick building material for recycling their waste, but due to tremendous increased in ash production many still piling up in ash valley.
Especially for Suralaya Coal Fired Plant, which operating since 1984 the problem with ash piling is crucial, the higher ash valley also related with higher risk of accident such as slope failure. The generation of soaring volumes of coal combustion products has become major concerns of utilities. According to Geological Agency of the Department of Energy and Mineral Resources (ESDM) Suralaya produces coal waste of 2.7 million tons per year and might reach up to 11.2 million tons in year 2027.

### 2. Potential of Earthquake in Indonesia

In Indonesia, the potential of earthquake-induced strong ground motion has gained significant attention following earthquake in Lombok, West Nusa Tenggara (NTB), followed by earthquake in Palu, Central Sulawesi and the latest happened in Situbondo, East Java with 6.0 in magnitude on October 10, 2018. Indonesia has thousands of volcanic mountains and located on the Pacific Ring of Fire, where tectonic plates can induces earthquake anytime when plates shift.
Suralaya Coal fired power plants (CFSPP) located north of Cilegon City, Banten as shown in above map. Based on earthquake building code in Indonesia or “Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung” SNI 1726:2012, the value of $S_s$ and $S_1$ that necessary to make response spectrum are 0.7-0.8 g and 0.3-0.4 g, respectively.

Figure 3. Suralaya Coal Power Plant Location (Googlemaps.com)

Figure 4. S, Based on earthquake building code in Indonesia or “Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung” SNI 1726:2012.
3. Potential Liquefaction of Fly Ash

The American Society for Testing and Materials (ASTM) standard C618 identifies two classes of fly ash. Class C fly ash is derived from the combustion of younger lignite or sub bituminous coal. It generally contains more than 20% of quicklime (CaO) and is self-cementing when mixed with water. Class F fly ash is derived from the combustion of older anthracite or bituminous coal. It contains less quicklime and is not self-cementing. Typical compositions of Class C and Class F fly ash are given in Table 1.

| Compounds          | Fly Ash Class |
|--------------------|---------------|
|                    | Class F       | Class C       |
| SiO₂               | 54.9          | 39.9          |
| Al₂O₃              | 25.8          | 16.7          |
| Fe₂O₃              | 6.9           | 5.8           |
| CaO (Lime)         | 8.7           | 24.3          |
| MgO                | 1.8           | 4.6           |
| SO₃                | 0.6           | 3.3           |

Overall, fly ash is a poorly-graded, fine-grained material. Fly ash particles are nearly spherical because they are formed by the solidification of molten minerals as they ascend the smokestack in a power plant (FHWA, 1999). Fly ash is collected in the smokestacks using water and the resulting slurry is hydraulically placed in stockpiles at landfills for subsequent land-filling. Generally, fly ash possesses a specific gravity of around 2.2 – 2.3, which is lower than the specific gravity of clay or sand due to the amorphous, glass-like crystalline structure of the silica. Depending on the particle size, hydraulic conductivities of reconstituted specimens of fly ash are around 1.0 x 10⁻⁵ cm/s. As a frictional material, the friction angle of fly ash typically ranges from 15 – 32 degrees, while the cohesion of fly ash is generally very low (< 0.05 psi).
Figure 6. Typical gradation curve for fly ash (after Kalinski and Hippley, 2005)

According to Besari et al. (1996), the chemical composition and mechanical properties of fly ash Suralaya (FAS) is presented in Table 2.

Table 2. Chemical composition and mechanical properties of FAS

| Chemical Composition | %     |
|----------------------|-------|
| SiO₂                 | 59.4  |
| Al₂O₃                | 24.7  |
| Fe₂O₃                | 4.6   |
| CaO                  | 3.1   |
| MgO                  | 1.7   |
| Na₂O                 | 2.5   |
| K₂O                  | 0.5   |
| TiO₂                 | 0.8   |
| P₂O₅                 | 0.4   |
| SO₃                   | NA    |
| Mn₃O₄                 | NA    |

Based on all the information above, it can be concluded that fly ash from Suralaya is fly ash type F.

Because spherical shape of fly ash particles, fly ash is susceptible to liquefaction. Liquefaction is defined as the transformation of a granular material from a solid to a liquefied state as a consequence of increased pore-water pressure and reduced effective
stress (Marcuson, 1978). Increased pore-water pressure is induced by the tendency of granular materials to compact when subjected to cyclic shear deformations. The change of state occurs most readily in loose to moderately dense granular soils with poor drainage, such as silty sands or sands and gravels capped by or containing seams of impermeable sediment.

In loose materials, the softening is also accompanied by a loss of shear strength that may lead to large shear deformations or even flow failure under moderate to high shear stresses, such as beneath a foundation or sloping ground. Loose soils also compact during liquefaction and reconsolidation, leading to ground settlement.

To help analyze the performance of fly ash material under dynamic loading, the method presented by Youd et al. (2001) regarding liquefaction resistance in soil deposits is adapted. This is considered an acceptable approach based on the similarity between fly ash and soil.

4. Prediction of Liquefaction

By utilizing the approach described above, the cyclic resistance ratio (CRR) can be estimated based on laboratory methods such as cyclic triaxial or cyclic simple shear. Cyclic resistance ratio (CRR) is a measure of liquefaction resistance, and is defined as:

\[
\text{CRR} = \frac{\tau_{\text{cyc}}}{\sigma_{vo}}
\]

(1)

Where:

\(\text{CRR}\) = Cyclic Resistance Ratio
\(\tau_{\text{cyc}}\) = The cyclic shear stress at liquefaction = \(0.65 \frac{a_{\text{max}} \sigma \gamma_d}{g}\)
(Seed & Idriss, 1971), “Simplified Approach”
\(\sigma_v\) = Total Stress
\(\sigma'_{vo}\) = The initial vertical effective stress

Where \(\tau_{\text{cyc}}\) is the cyclic shear stress at liquefaction (when effective stress in the material reaches zero), and \(\sigma'_{vo}\) is the initial vertical effective stress prior to cyclic loading.

To calculate the factor of safety against liquefaction for horizontally layered sites, the CRR is divided by the cyclic stress ratio (CSR), which is dependent on anticipated peak ground surface acceleration, \(a_{\text{max}}\), due to earthquake loading (Seed and Idriss, 1971):

\[
\text{CSR} = 0.65 \frac{a_{\text{max}} \sigma \gamma_d}{g \sigma'_w}
\]

(2)

Where:

\(\text{CSR}\) = Cyclic Resistance Ratio
\(a_{\text{max}}\) = Peak Ground Surface Acceleration
\(\sigma_v\) = The total vertical effective stress
\(\gamma_d\) = A stress reduction coefficient to account for soil deformability
\(g\) = The gravitational acceleration constant
\(\sigma'_{vo}\) = The initial vertical effective stress
\(\text{FS}\) = Factor of Safety

Where \(\sigma_v\) is the total vertical stress, \(\gamma_d\) is a stress reduction coefficient to account for soil deformability, and \(g\) is the gravitational acceleration constant.
To equate transient field shaking to cyclic laboratory shaking, a factor of 0.65 is introduced. Since the method used to calculate the factor of safety is based on an earthquake magnitude of 7.5, the equation is adjusted using a magnitude scaling factor. To account for variations in shaking duration caused by earthquakes of different magnitudes. Additionally, Seed and Idriss introduced the relation between percent fines in soil and liquefaction-resistance.

The same approach was applied to this research with the expectation that the percentage addition of waste products will effectively increase fly ash resistance against earthquake loading.

\[ \text{Figure 7. Correlation between equivalent uniform cyclic stress ratio and SPT } (N_{\text{160}} - \text{Value for events of magnitude } M \approx 7.5 \text{ for varying fines contents, (Youd, et al, 2001).}) \]

Based on Youd, et al., (2001), correlation between equivalent uniform cyclic stress ratio (CSR) and Standard Penetration Test (SPT) for Magnitude (M) = 7.5 for varying fines contents, with adjustments at low cyclic stress ratio as recommended by the National Center for Earthquake Engineering Research (NCEER) working group.

Due to scarcity of land around power plants, one option for increasing the capacity of an ash pond is by raising its height. In many places the total height of the deposit is higher than 30 m. The ash deposit placed in slurry form has a very low density and leads to problems such as liquefaction during earthquakes, poor bearing capacity, large settlement, etc.

Considerable research has been conducted to improve the density of ash by different techniques such as vacuum dewatering, electro osmosis, vibro-compaction, stone columns, blasting, etc. (Gandhi, et al, 1999).

There are also three (3) common field methods used to evaluate liquefaction resistance, in terms of CRR: standard penetration test (SPT); cone penetration test (CPT), and shear wave velocity.

Problem is there are difficulties to take measurement using SPT, CPT and shear wave velocity of ash embankment such as difficulty to bring the instruments on the field and difficulty to take undisturbed samples.

To help predict factors of safety against liquefaction, this paper will use equations from Susilo (2016) to approximate cyclic resistance ratio (CRR) using cyclic stress ratio (CSR).
Class F fly ash \( CRR = \sqrt{(0.4536CSR^{-2.763}) \times 1.69} \) (3)

To show how the equations works, below is an example to find factor of safety using all zones where coal power plants located (Suralaya, Lontar, Labuhan, Pelabuhan ratu, and Adipala) using predicted peak ground acceleration (PGA), on hard rock using earthquake building code in Indonesia or “Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung” SNI 1726:2012 and to predict the factor of safety using CRR from equations. The procedure for this example is shown below. To find CSR in this example, \( a_{max} \) value is based from SNI 1726:2012 and \( \gamma_{sat} \) value is from Susilo (2016). The calculated CSR value will be used as an input for equation to get CRR and find factor of safety against liquefaction.

Seismic Source: SNI 1726:2012

Landfill Location: Suralaya, Lontar, Labuhan, Pelabuhan ratu, and Adipala

Earthquake Magnitude: 7.5 (Assume to make MSF = 1)

\[
FS = \frac{CRR}{CSR} \quad (MSF = 1)
\]

Depth = 0 m (in ground level)

Height of embankment = 10 m (Fully saturated)

Assumption of ground level elevation ± 0.00 meter

| Input data |
|------------|
| \( a_{max} \) | PGA (g) |
| \( r_d \) | A stress reduction coefficient to account for soil deformability |
| \( g \) (m/s\(^2\)) | = 9.81 |
| \( \gamma_{water} \) (kg/m\(^3\)) | = 1000 |

Information to calculate factor of safety (SF) for all locations in predicted peak ground acceleration (PGA) is listed above.

| Table 3. Factor of Safety for all locations in predicted peak ground acceleration (PGA) |
|----------------------------------------|
| Material = Class F fly ash |
| Location | \( a_{max} \) | \( \gamma_{sat} \) | \( \sigma_v \) | \( \sigma_{vo} \) | \( \tau_{cyc} \) | CSR | CRR | FS |
|----------|--------|--------|--------|--------|--------|-----|-----|-----|
| Suralaya | 0.40   | 128.46 | 0.022  | 225.07 | 10336.1|
| Lontar   | 0.40   | 128.46 | 0.022  | 225.07 | 10336.1|
| Labuhan  | 0.60   | 1590.15| 15897.5| 5899.68| 3935.4 |
| Pelabuhan ratu | 0.60 | 192.71 | 0.033  | 128.54 | 3935.4 |
| Adipala  | 0.50   | 160.58 | 0.027  | 165.36 | 6075.3 |

The Peak Ground Acceleration (PGA) on the example used data from earthquake building code in Indonesia or “Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung” SNI 1726:2012.
Figure 8. Predicted peak ground acceleration (PGA), on hard rock from earthquake building code in Indonesia or “Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung” SNI 1726:2012.

Factor of Safety (FS) has a scaling factor to the CRR with respect with earthquake magnitude (Magnitude Scale Factor, MSF).

As for example the magnitude used is 7.5 and based on Figure 9. using data from Seed et al. (2001); the CRR use on the example should be multiply with a factor of 1.

Figure 9. Comparison of Published CRR Weighting Factors

5. Conclusion
From the example above, it shows that all impoundment facilities are not at risk for liquefaction. The location of all this impoundment already considered to be built not close to any source of earth fault which can generate very high magnitude of earthquake. By using the same equation, any power plant can calculate how high their impoundment to be built and for whoever want to build power plant can predict the safety factor of their future ash impoundment facility
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