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Evaluation of erosion vulnerability for river levee material using physico-chemical properties of soil focusing on torrential rainfall due to climate change

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ABSTRACT: Recently, the occurrence of natural disaster due to climate change has been increasing. Hurricane Katrina which occurred on August, 2005 caused severe damage to some areas in New Orleans leading to collapse of sea dike and river levee. The collapse of river levee is caused by the overtopping and then river levee material is easily eroded by flowing water on the river levee. Recently, the numbers of torrential rainfall have markedly been increasing in Japan. Those increasing frequency of heavy rainfall also induced collapse on the river levee in Niigata prefecture on July, 2004 and the effective assessment the vulnerability of erosion is paramount. Erosion mechanism caused by overtopping and boiling depends on physico-chemical soil properties of soil such as liquid limit, natural water content, grain size, soil particle density and cohesion. This study made an attempt to evaluate the vulnerability of erosion of some river levee materials by using these soil properties and to propose a method for evaluating the vulnerability of river levee material. It is indicated from these evaluations that the river levee materials in Kanto area are stronger against erosion than those in Kyusyu area. The results are demonstrated on the maps of the evaluated vulnerability of erosion and the method of countermeasure against the climate change induced damage in therepresentative river levees in Japan were proposed.

Keywords: Erosion, river levee, Rf, wL-wn

1. Introduction

Global warming causes the temperature rise. The Fourth Assessment Intergovernmental Panel on Climate Change (IPCC Report 2007) described if we do not take any preventive measures to restrain global warming, global temperature will rise by 6.4 degrees. The report also predicted a warming of about 0.2 degrees per decade for the next two decades. Furthermore global warming causes the climate change; huge hurricane, typhoon, drought, and so on. The Japan Meteorological Agency observed that the numbers of torrential rainfall from 1979 to 2006 were remarkably increasing. Those increasing caused lots of disasters on the river levee as well as on the coastal embankment. The IPCC (2007) reported the influence of global warming to the river levee is getting serious. Torrential rainfall makes water level high on the river levee and causes overflow and erosion on the slope of river levee. Overflow is one of the influencing factors on erosion on the river levee. For example, the Hurricane Katrina which occurred August 29th, 2005 caused severe damage to some areas in
New Orleans leading to collapse of sea dike and river levee (Fig.1). Therefore it is necessary to evaluate the vulnerability of erosion of river levee.

This paper considered erosion mechanism of the river levee and proposed a method for evaluation of the vulnerability of erosion using physico-chemical properties of soil.

2. Erosion mechanism

The main factors of erosion are weather conditions (wind, rainfall, especially intensive rainfall), geographical features (slope, landform), planting treatment and physico-chemical properties of soil. This study focused on physico-chemical properties of soil to evaluate the vulnerability of erosion. When erosion occurs in river, soil particle have received share stress of flowing water and then physico-chemical properties of soil (weight of soil particle, binding force between soil particles, cohesion and so on) resist it. Weight of soil particle under water is given by Eq.1.

\[ W = \frac{\pi}{6} d^3 (\rho_s - \rho_w) g \]  

where \( W \)=weight of soil particle under water(N); \( d \)=grain size(m); \( \rho_s \)=soil particle density (kg/m\(^3\)); \( \rho_w \)=water density (kg/m\(^3\)); \( g \)=gravitational acceleration (m/s\(^2\)). The occurrence condition of erosion is given by Eq.2.

\[ \tau_e A = \left( \mu' + \mu \right) W \]  

where \( \tau_e \)=critical share stress that is the lowest stress to move soil particle(N); \( A \)=maximum cross section of soil particle(m\(^2\)); \( \mu' \)=coefficient of binding force
between soil particles; \( \mu^* = \text{coefficient of cohesion} \). Namely, critical shear stress is given by Eq. 3.

\[
\tau_c = \frac{2}{3} d (\rho_s - \rho_w) g \left( \mu' + \mu^* \right) (3)
\]

In the case of sand particle, \( \mu' \) is high because the size of sand particle is large and binding force between soil particles is also strong. On the other hand, in the case of clay particle, \( \mu^* \) is high because the size of clay particle is small and cohesion which has the electromagnetic and electrostatic interparticle forces between soil particles is also strong. Therefore erosion mechanism on slope of river levee is as follows (1) sand particles are hardly eroded because of strong binding force, on the other hand, silt and clay particles have strong cohesion around the soil particles, therefore they are eroded at the early stage. (2) when most silt and clay particles are eroded around sand particles, binding force and cohesion decrease and sand particles are eroded. (3) erosion makes progress while repeating (1) and (2) Fig. 2 shows erosion mechanism. According to Briaud (1999) and Sekine (2001), fine-grained soil which has cohesion is eroded particle to particle at a low flow velocity and is eroded block to block at a fast flow velocity.

![Fig.2 Erosion mechanism](image-url)
3. Method for evaluation of the vulnerability of erosion 3), 4), 5)

We proposed the method for evaluation of the vulnerability of erosion using physico-chemical properties of soil.

1) Method for evaluation of the vulnerability of erosion using weight of soil particle

Soil consists of various sizes of particles (sand, silt, and clay) and has a variety of the resistance force for erosion. To evaluate the vulnerability of erosion using weight of soil particle, we calculated weighting coefficient using the result of residual mass percentage of grain size distribution test and defined resistance value of erosion ($R_{fe}$). The value is given by Eq.4.

$$R_{fe} = \sum_{i=1}^{n} \frac{\pi}{6} d_i^3 (\rho_s - \rho_w) g (P_i - P_{i-1}) / 100$$

where $R_{fe}$ = resistance value of erosion (N); $d_i$ = grain size of number $i$ (m); $P_i$ = accumulation residual percentage of number $i$ (%). Soil material which has low $R_{fe}$ is weak for erosion.

2) Method for evaluation of the vulnerability of erosion using liquid limit and natural water content

We proposed previously method for evaluation of the vulnerability of erosion using weight of soil particle. Nevertheless, in the case of fine-grain soil which has cohesion, it is difficult to evaluate the vulnerability of erosion using resistance value of erosion and new index is necessary. This study focuses on liquid limit and natural water content. Fine-grain soil changes its characteristic from plastic state to liquid state as water content increases, and its resistance force for erosion becomes low. Therefore, soil material which has high liquid limit is strong for erosion. At this time, focusing on slope of river levee, torrential rainfall raises water level of river and soil material in natural water content reaches liquid limit. It changes its characteristic to liquid state and erosion happens. Consequently, it is possible of evaluate of the vulnerability of erosion about fine-grain soil using difference between liquid limit and natural water content ($w_L - w_n$). If soil material which has low $w_L - w_n$ receives share stress, it is easily eroded as it changes its characteristic immediately from plastic state to liquid state. Indeed, according to
Otsubo (1985) and Sekine (2000), erosion rate increases as water content rises; therefore, this index is reliable to evaluation of the vulnerability of erosion.

4. Evaluation of some river levee material

To evaluate of the vulnerability of erosion using resistance value of erosion and \( w_L - w_n \), some river levee materials were gathered from various places in Japan. Table 1 shows the data about sample name, sampling area, physico-chemical properties of soil (particle density, natural water content and liquid limit), \( w_L - w_n \) and resistance value of erosion. Fig. 3 shows grain size accumulation curve of river levee materials used in this study. Primary Shirasu and Secondly Shirasu showed NP as a result of liquid limit and plastic limit test; therefore we couldn’t calculate \( w_L - w_n \). However, the river levee materials have low content of fine-grain soil, and the influence of eroded fine-grain soil to river levee is relatively low. Therefore, this study evaluates the vulnerability only using resistance value of erosion. As a result, the resistance value of erosion of primary Shirasu is lower than those of Secondly Shirasu and primary Shirasu is easily eroded compared with Secondly Shirasu. The other river levee materials were evaluated as Fig. 4 shows. Fig. 4 has \( w_L - w_n \) on x-axis and resistance value of erosion on y-axis. The smaller the values of x-axis and y-axis are, the weaker the river levee material are. Kanto-loam is comparatively strong for erosion. Akaboku is comparatively weak for erosion. Ebetsu is stronger than Akaboku but weaker than Kanto-loam.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Sampling point</th>
<th>( \rho_r ) (kg/m^3)</th>
<th>( w_n ) (%)</th>
<th>( w_L ) (%)</th>
<th>( w_L - w_n ) (-)</th>
<th>( R_{ef} ) (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanto-loam</td>
<td>Mito area in Ibaraki prefecture</td>
<td>2.691×10^3</td>
<td>100.7</td>
<td>140.3</td>
<td>39.6</td>
<td>3.95×10^7</td>
</tr>
<tr>
<td>Kuroboku</td>
<td>Tyogoono area in Ooita prefecture</td>
<td>2.616×10^3</td>
<td>77.5</td>
<td>97.0</td>
<td>19.5</td>
<td>6.89×10^8</td>
</tr>
<tr>
<td>Akaboku</td>
<td>Tyogoono area in Ooita prefecture</td>
<td>2.692×10^3</td>
<td>95.7</td>
<td>105.8</td>
<td>10.1</td>
<td>4.31×10^8</td>
</tr>
<tr>
<td>Primary Shirasu</td>
<td>Tagami area in Kagoshima prefecture</td>
<td>2.460×10^3</td>
<td>14.6</td>
<td>NP</td>
<td>NP</td>
<td>6.13×10^7</td>
</tr>
<tr>
<td>Secondly Shirasu</td>
<td>Tagami area in Kagoshima prefecture</td>
<td>2.630×10^3</td>
<td>16.6</td>
<td>NP</td>
<td>NP</td>
<td>1.19×10^6</td>
</tr>
<tr>
<td>Shinano river levee material</td>
<td>Shinano river levee in Niigata prefecture</td>
<td>2.610×10^3</td>
<td>21.7</td>
<td>33.5</td>
<td>11.8</td>
<td>2.55×10^7</td>
</tr>
<tr>
<td>Tsuishikari river levee material</td>
<td>Tsuishikari river levee in Hokkaido prefecture</td>
<td>2.596×10^3</td>
<td>23.1</td>
<td>44.3</td>
<td>21.2</td>
<td>4.99×10^8</td>
</tr>
<tr>
<td>Ebetsu</td>
<td>Ebetsu area in Hokkaido prefecture</td>
<td>2.648×10^3</td>
<td>21.5</td>
<td>41.6</td>
<td>20.1</td>
<td>2.48×10^7</td>
</tr>
</tbody>
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Shinano river levee materials have low value of $w_{L-w_n}$ and there fine-grained soil is easily eroded. Kuroboku and Tsuishikari river levee materials have low value of $R_e$ and their coarse-grained soil is easily eroded. Fig. 5 is the map of the vulnerability of erosion and measures of against erosion. Tsuishikari river bank material has characteristics dangerous for erosion in brief evaluation and it is necessarily to reinforce slope like some bank protection works. Ebetsu is safety for erosion than Akaboku but dangerous than Kanto-loam. Niigata area has characteristics fine-grained soil is easily eroded and it is necessarily doing bank protection work. Kanto area is comparatively safety. Kuroboku has characteristics slope is easily eroded and Akaboku also dangerous, it is necessarily to reinforce slope like some bank protection works.

![Fig.3 Grain size accumulation curve about river levee material](image)

![Fig.4 Vulnerability of erosion about some river levee material](image)
5. CONCLUSION

We proposed a new index which was made by combining the resistance value of erosion ($R_{fe}$) river levee materials and the difference between liquid limit and natural water content ($w_{L}-w_{n}$). Using these indexes, we compared some river levee materials for the vulnerability of erosion.

(1) From the resistant value of erosion, it was found that primary Shirasu is weaker than Secondly Shirasu.

(2) As Fig.4 shows, it was found that Kanto-loam is comparatively strong for erosion.

(3) As Fig.4 shows, it was found that Akaboku is comparatively weak in erosion.

(4) As Fig.4 shows, it was found that Ebetsu is stronger than Akaboku but weaker than Kanto-loam.

(5) As Fig.4 shows, it was found that Shinano river levee materials have low value of $w_{L}-w_{n}$. This indicates that fine-grained soil is easily eroded.
(6) As Fig.4 shows, it was found that Kuroboku and Tsuishikari river levee materials have low value of $R_f$ and their coarse-grained soil is easily eroded.

(7) The vulnerability of erosion map and countermeasures against erosion in Japan was made. River levee materials which are weak for erosion may collapse when overflow occurs. In this case we have to take measures such as bank protection works and planting treatment.

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