Change of Soil Properties in the Bengawan Solo River Embankment due to Drying–Wetting Cycles

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ABSTRACT: This paper studies the behavior of Bengawan Solo River embankment soil properties for both in-situ and laboratory conditions. In the laboratory, series of cyclic drying and wetting tests were carried out to clarify the changes of in-situ soil properties over time since the soil had been initially compacted. Maximum dry density from Standard Proctor test was applied as initial compacted condition. Three cycles of drying and wetting were used to represent three cycles of dry and rainy seasons. The in-situ soil investigation was carried out during seasons. The results show that the investigated in-situ soil properties were in good agreement with the laboratory test results at the 2nd and 3rd cycles. It denotes that these number of cycles are required to achieve the similar condition as in-situ soil. In addition, by observing the rate of change in soil properties, it was possible to trace back the construction time of the river embankment.

KEYWORDS: River embankment, Drying-wetting cycle, Compaction, In-situ investigation

1. INTRODUCTION

At the end of 2007 and in the beginning of 2008 and 2009, heavy rainfalls occurred in the upstream area of the Bengawan Solo river (Central of Java Province, Indonesia). Flooding occurred in the downstream area (East Java Province, Indonesia), including the research observation site. The floods had overtopped the river embankment and further continued to the residential area. More than one thousand civilians were evacuated to secure the area. The most destructive floods occurred in the beginning of 2009. These floods affected most of the area in Kanor district of Bojonegoro city. Reported by the government, several million dollars had been lost due to damaged property that included more than a thousand houses and farmlands. In addition, a hundred schools and offices were flooded and river embankments were collapsed. Although the main cause of the floods was the heavy rainfall in the upstream area, other factors, such as sedimentation in the riverbed, improper operation of the reservoir gate, diverted function of the catchment area into the farm land, and the unprotected river embankment, also contributed to the flooding.

After 2009, no destructive flooding has occurred. However, during heavy rainfall, the observed water level has risen to just below the top of the river embankment. For this reason, a policy has been initiated by the government to re-elevate river embankments based on the prediction of the potential peak rainfall, up to one hundred years in the future. During the re-elevation, the soil material for the embankment had been initially compacted using a Standard Proctor compaction effort. Roller compaction had been preferred as field compaction method for fulfilling this effort. River embankments will guarantee favorable performance if this initial condition is well maintained. The actual issue is we cannot keep the best condition at the initially constructed. In addition, we should know the time period when the embankment starts to lose their best condition. The answer of this question may have been ignored for long time.

It is commonly known that the initial soil properties may change throughout a year due to the cycles of the seasons (dry and rainy seasons). Thus, the stability of the river embankment also changes over time due to the changes in the soil properties. If the changes continue to be unmonitored, the failure of the river embankment will occur at some places in the future, most likely during the rainy season. Therefore, a proper method for evaluating the changes in the soil properties needs to be established.

In this paper, the study is focused on the change, as well as the rate of change, of the soil properties of a river embankment as a function of time. A laboratory test and an in-situ investigation were carried out. Series of cyclic drying and wetting tests were conducted in the laboratory using recovered soil from the actual site to evaluate the changes in its physical and mechanical properties. As in-situ investigation, the physical and mechanical soil properties were investigated by using intact samples derived from surficial soil, and suction properties were investigated by performing a field suction test on surficial soil. In-situ investigation of soil properties was performed to clarify the rate of change in the soil properties. After the rate is established, it was possible to trace back the initial construction time of the river embankment.

2. RIVER EMBANKMENT DESCRIPTION

2.1 Observation Site

The Bengawan Solo river is the longest river on Java Island, which is located along the Center of Java and East Java provinces. It is approximately 600 km in length and has a 16,000-km^2 catchment area. It passes through 17 districts and 3 cities in both provinces. In addition to collecting water, the river is also used as drinking water, for farming, sand mining, transportation, and home industry needs. Figure 1 shows the Bengawan Solo river path, including the research observation site that is located in the Kanor district of Bojonegoro city, East Java Province.

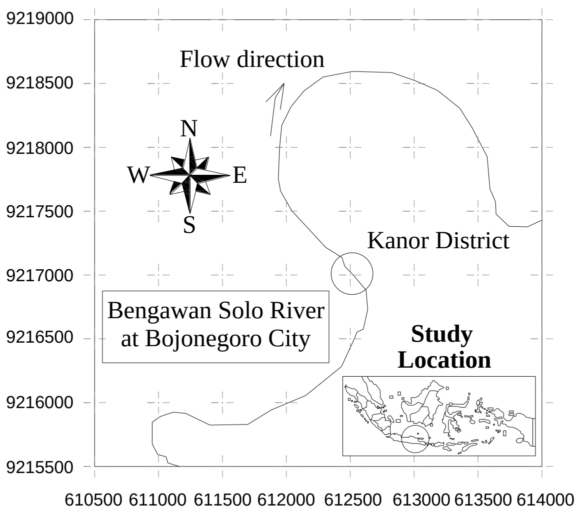


Figure 1 Research study location
(abscissa and ordinate in unit of meters)

Water in the upstream area of the river is sourced from several other rivers and collected by the "Gajah Mungkur" water reservoir. Large amount of sedimentation, that occurred in upstream area, reduced river capacity and subsequently transported the excessive water into Bengawan Solo river. This triggered the flooding of the river, and also endangered the stability of the river embankment.

2.2 History of Embankment Failure

Since 2005, embankment failure most frequently has occurred where shallow-slip slope failure and slope improvement failure were taken place along the river path. All of embankment failures are predicted to be occurred due to water level fluctuation during dry and rainy seasons.

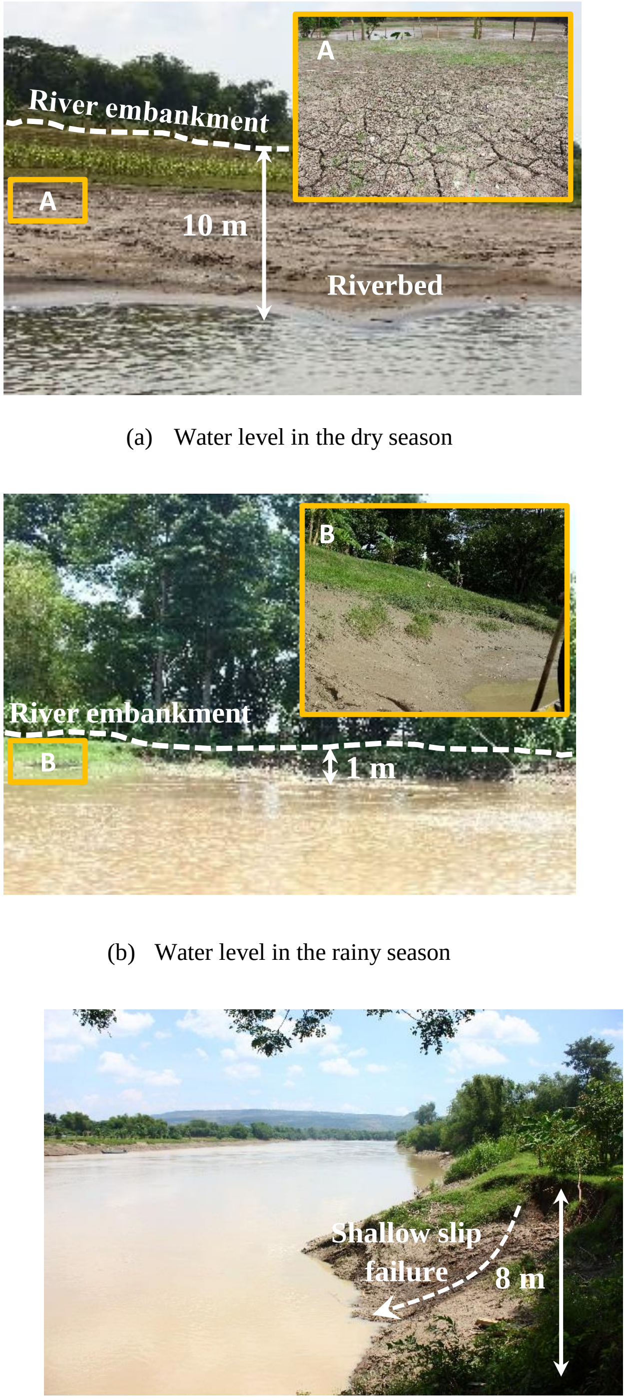
Mountassir et al. (2010) expressed that the Bengawan Solo river water level at Kedungharjo village, Tuban city near Bojonegoro city fluctuated by as much as 10 m between dry and rainy seasons. Figure 2.a. shows the river water level during the dry season. The water level was so low and even the riverbed could be seen directly in the field. Soil cracks were discovered due to the evaporated water during this period. Figure 2.b. shows the river water level during the rainy season. During this period, the water level was high enough to almost reach the top of the river embankment. In addition, the soil was soft and weak owing to the abundance of water. Figure 2.c. shows the recent shallow-slip slope failure at Semambung village, Kanor district, Bojonegoro city on March 11, 2014. Until recently, the shallow slip failure still occurred annually during the peak rainy season.

2.3 History of Construction Process

In the past, the government decided to build a man-made embankment owing to the large population of civilians who chose to live near the river embankment. Furthermore, when flood disasters had occurred three years in a row (2007, 2008, and 2009) and many areas were inundated afterwards, the government decided to re-elevate the embankment in 2011. Indeed, there is a minimum requirement of selected embankment material for re-elevating purposes.

In 2004, the Ministry of Public Works and Housing of Indonesia issued a technical specification (Pd T-16-2004-A) which mainly acquires non-cohesive soil with certain properties for embankment material.

However, in fact, lots of embankment material, which are generally dominated by fine grained soil, have been deposited in the riverbed due to river embankment failure and river sedimentation.



(a) Water level in the dry season

(b) Water level in the rainy season

(c) Shallow slip failure on March 11, 2014

Figure 2 River embankment at Kanor district

Therefore, due to the abundant riverbed material and certainly for efficiency reason, the government preferred to utilize this existing riverbed material for re-elevating the river embankment. This material was removed from the riverbed and layered on the embankment during the dry season. The dry season was preferable for this activity due to workability reasons during construction. The maximum value of Standard Proctor compaction effort was applied as specification of the compaction method. Roller compaction had been preferred as field compaction method for fulfilling this effort. In addition, for transportation and accessibility reasons, this compaction method was preferred rather than using large compaction equipment.

2.4 Actual Issues of River Embankment

An excavating, remolding and recompacting processes induce an unsaturated soil condition (Fredlund, D.G. and Rahardjo, H., 1993). It implies that embankment compaction induces an unsaturated soil condition. Certainly, the unsaturated soil condition has significant influence on slope stability (Fan, Ch and Hsiao, Ch., 2010).

The important issue with the compacted river embankment is that the soil properties might change and become more likely to lose their initial compacted condition owing to changeable and repetitive seasons over several years. In order to determine when the soil properties of the embankment began to lose their initial compacted condition, it was necessary to re-create the phenomenon exactly as it was constructed in the past.

To simulate the cycles of dry and rainy seasons as changeable seasons on the river embankment, the cyclic drying–wetting test was performed at the laboratory by using recovered soil from field. Then, the initial compacted condition was modeled by using the maximum dry unit weight and optimum water content obtained from the Standard Proctor test results. Remolding process in the laboratory is later needed to create samples for cyclic drying-wetting test. To clarify the rate of soil properties change due to the cyclic drying-wetting test, an in-situ investigation was also performed.

3 METHODOLOGY

3.1 In-Situ Investigation

In order to clarify the property changes of dried and wetted soil, an in-situ investigation was performed in every 2 weeks for 4 months, starting in January 2014 and ending in April 2014. January 2014 was in the middle of the rainy season, February 2014 was in the peak rainy season, March 2014 was at the end of the rainy season and April 2014 was at the beginning of the dry season. The physical and mechanical soil properties were investigated by using intact soil samples, and soil suction was investigated by performing a field suction test. For the embankment that was going to be investigated, the surface soil layer of the river embankment had been selected for object of investigation as it always experiences drying and wetting conditions during changes in the seasons.

3.2 Intact Soil Sampling

The tube used for intact soil sampling was 7.62 cm in diameter and 60 cm in length. Firstly, brush was removed from the top soil in a 50 cm × 50 cm area. Then, the tube was manually pressed on the ground. The starting penetration depth was 0.50 m below the top soil, and the tube was removed after achieving the designated depth. To maintain the undisturbed condition, both sides of the tube were sealed with liquid wax and plastic sealer. Filled-soil tubes were then brought to the laboratory for investigating the physical and mechanical properties.

3.2.1 Field Suction Test

The field suction test was regularly monitored to obtain soil matric suction by using the filter paper method. Many researchers have used filter paper method (Gardner, 1937; Marinho and Oliveira, 2006; Bulut and Leong, 2008). The contact filter paper, which used in this research, is one of the method that defines the water content of filter paper as the soil matric suction (Fredlund, D.G. and Rahardjo, H., 1993). Whatman filter paper was used in this method. In addition, the calibration curve of filter paper was also used to correlate between the water content of filter paper and the related matric suction value.

Prior to use, the Whatman filter paper was protected with ordinary filter paper on both sides so that it comprised three stacks of filter paper in total. During the in-situ investigation, first a 50 cm × 50 cm area of the surface soil layer of the river embankment was cleared from brushes. The soil was dug to 50 cm depth, and then Whatman filter paper was placed inside. Furthermore, the dug soil was returned back into the hole for maintaining the original condition. Filter paper had been allowed to be left in for 6 hours before it was taken out.

In addition to the regular field suction test, an additional field suction test was considered to be conducted to determine the reason why the surface soil layer was selected as the object of investigation. Therefore, matric suction measurements using the Whatman filter paper method were performed vertically at several points, starting from the lower part and gradually moving toward the upper part of surface soil layer of the river embankment. It was measured at the following elevation depths: ± 0.0 m, -0.6 m, -1.2 m, -1.5 m, -1.8 m, -2.1 m, -2.4 m, and -2.7 m (measured from original ground level).

All of the field suction tests were using filter paper method that measured in the laboratory. Sets of the suction test, which started from placing the filter paper in the field until weighing at laboratory, were conducted under the similar humidity and temperature. The humidity ranged between 70-80 % and temperature ranged between 27-30 degree of celsius.

3.2.2 Soil Properties of In-Situ Condition

The investigated physical soil properties at in-situ condition were as follows: dry unit weight, water content, void ratio, and saturation degree. The investigated mechanical soil properties were as follows: undrained cohesion derived from an unconfined compression strength test and soil suction derived from a field suction test. All of the physical soil properties and undrained cohesion were tested by using intact soil samples collected during the in-situ investigation.

3.3 Cyclic Drying–Wetting Test

3.3.1 Compaction Test for Determination of Initial Compacted Soil Condition

Standard Proctor compaction test was performed to determine the maximum dry unit weight and optimum water content values which used for the initial compacted soil condition. Disturbed soil taken from surface soil layer in the river embankment was used in this test. Prior to the test, eight soil samples with various water contents were homogeneously mixed and cured for 4 days. Furthermore, these samples were statically compacted according to the method of standard Proctor compaction test.

3.3.2 Soil Sample Preparation

For remolding soil, by using compression machine, the soil samples were statically compacted according to the initial compacted soil condition. The static compaction method in laboratory was selected in order to have similar method applied in the field (roller compaction). The soil was remolded using a PVC mold as shown in Figure 3. The remolded soil has dimension in accordance to the soil sample test requirement. A volumetric-gravimetric test required the sample to be of 3 cm height and 3.5 cm diameter, and the unconfined compression test required the sample to be of 8 cm height and 3.5 cm diameter.

3.3.3 Drying–Wetting Procedure

The cyclic drying and wetting test of the remolded soil samples was performed in the laboratory by adjusting the water content of the samples. Similarly, as it had been investigated previously by Kalkan, 2011 and Al-Homoud et al., 1995, the wetting and drying test was completed by inundating soil sample with the water as wetting test and then continued to air-dry the soil sample as drying test.

The difference between the previous research and this research is the wetting process. In this research, the water was gradually added until saturated condition was reached. This gradual process was necessary because of the river water level in the field also gradually fluctuates throughout the dry and rainy seasons. Meanwhile the drying process was performed by aerating the samples under open-air environment and sun heat.

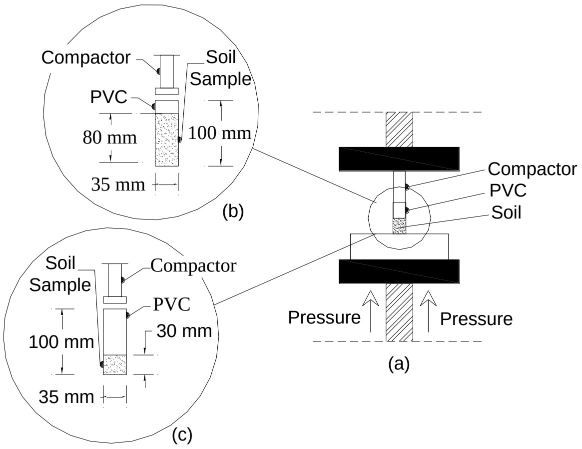


Figure 3 Remolding soil sample (a) compression machine; (b) soil sample dimension of unconfined compression test; (c) soil sample dimension of volumetric-gravimetric test

In this research, for equalizing the dry and rainy seasons in the field that occur annually on the river embankment, the maximum limit of water content during wetting process (saturated water content) and the minimum limit of water content during drying process (air-dry water content) were required.

Water content upon when the soil sample achieved its driest condition under air-dry environment was defined as the air-dry water content, and water content when the soil sample achieved the wettest condition was defined as saturated water content.

There were two steps for obtaining air-dry water content. The first step was oven heating, and the second step was aerating in an open-air environment. In the first step, the oven was used to heat the soil to 30 °C until it achieved equilibrium. Equilibrium means that the water content does not change with successive measurements. This condition took seven days to achieve. The second step was the soil sample aeration under open dry air environment until the equilibrium condition was reached. This process also took seven days. At the end of the second step, the soil was sampled to observe the value of the water content. This observed water content w_c was then defined as the air-dry water content.

For obtaining the saturated water content, the soil sample was wetted until it achieved the saturated sample condition (S_r = 100 %). As a result, the air-dry water content was 7.09 % and the saturated water content was 37.83 %. These water contents were measured under similar humidity and temperature, where humidity ranged between 70–80 % and temperature ranged between 27-30 degree of celsius.

To perform the gradual change of drying and wetting, there were step series that determined from the range of air-dry water content and saturated water content values. These step series controlled the drying and wetting process of the soil sample by using water content as the criterion value to be achieved. As many as ten step series were created in the range between air-dry water content and saturated water content values. The water content value for each of step was derived from the calculation of water content difference (Δw) that divided by 10 as the number of steps. The water content difference (Δw) was defined as the difference between saturated water content and air-dry water content values. The water content value for each step is indicated with an index number as shown in Table 1.

As a term, each of the drying step series were indexed with the letter "D", while wetting steps series were indexed with the letter "W". This letter was then followed by the index number, for example D5 is for drying at water content 19.39 % and W5 is for wetting at water content 19.39 %. In addition, there was water content at initial compacted condition that is defined as initial in the step index number as shown in Table 1. It needs to be considered due to all soil samples start their drying wetting process from the initial compacted condition.

Table 1 Water Content for Each Drying– Wetting Step Series

Drying–Wetting Process	
Step Index Number	Water Content, w_c (%)
1	7.09
2	10.17
3	13.24
4	16.31
5	19.39
6	22.46
7	25.54
Initial	27.19
8	28.61
9	31.68
10	34.76
11	37.83

The process to achieve the air-dry water content condition and then continues to achieve the saturated water content condition, was defined as one cycle of drying and one cycle of wetting. In this research, three cycles were chosen, which represents to the three cycles of dry and rainy seasons in the field or in-situ condition.

In detail, the soil sample at 1st cycle of drying was started to be dried from initial (w_c 27.19 %) until D1 (w_c 7.09 %), it means that the sample was gradually dried from condition of initial-D7-D6-D5-D4-D3-D2-D1, then the following process is the 1st cycle of wetting that the sample was started to be wetted from W1 (w_c 7.09 %) until W11 (w_c 37.83 %), it means that the sample was gradually wetted from condition of W1-W2-W3-W4-W5-W6-W7-W8-W9-W10-W11. The next process is the 2nd cycle of drying when the sample was started to be dried from D11 (w_c 37.83 %) until D1 (w_c 7.09 %), it means that the sample was gradually dried from condition of D11-D10-D9-D8-D7-D6-D5-D4-D3-D2-D1, then the following process is the 2nd cycle of wetting that the sample was started to be wetted from W1 (w_c 7.09 %) until W11 (w_c 37.83 %), it means that the sample was gradually wetted from condition of W1-W2-W3-W4-W5-W6-W7-W8-W9-W10-W11. The next process is the 3rd cycle of drying when the sample was started to be dried from D11 (w_c 37.83 %) until D1 (w_c 7.09 %), it means that the sample was gradually dried from condition of D11-D10-D9-D8-D7-D6-D5-D4-D3-D2-D1, then the last process is the 3rd cycle of wetting that the sample was started to be wetted from W1 (w_c 7.09 %) until W11 (w_c 37.83 %), it means that the sample was gradually wetted from condition of W1-W2-W3-W4-W5-W6-W7-W8-W9-W10-W11. During drying and wetting test, the samples were turned upside down and vice versa to maintain the samples homogeneity. The elapsed time for one cycle of drying and wetting at the laboratory was approximately ± 4 days.

3.3.4 Soil Property Test after Drying and Wetting Test

In each step at all cycles, the dried–wetted soil samples underwent sets of laboratory test to determine their physical and mechanical soil properties. The physical properties of the dried and wetted soil were as follows: dry unit weight, water content, void ratio, and saturation degree. The mechanical properties of dried and wetted soil were as follows: undrained cohesion derived from unconfined compression strength test and soil suction.

4 RESULTS AND DISCUSSION

4.1 Distribution of Matric Suction at Surface Soil Layer

Figure 4 shows the distribution of matric suction that was measured from the lower part to the upper part of surface soil layer of the river embankment, as the result of additional field suction test.

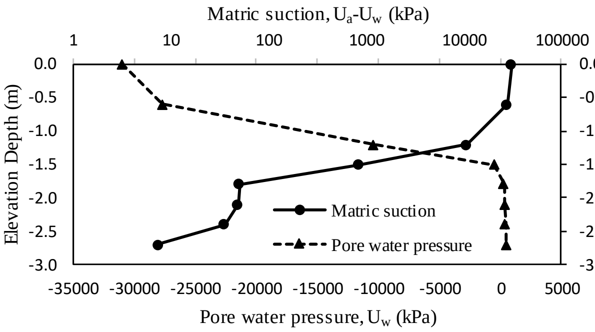


Figure 4 Suction distribution on soil layer surface

Fawcett and Collis-George (1967) and McQueen and Miller (1968) in Fredlund, D.G. and Rahardjo, H., 1993 revealed that application of filter paper method could handle a wide range of suction value, from few kilopascals to several hundred thousand kilopascals.

The additional field suction test result shows that the matric suction distribution was varied from 10–10^5 kPa. This high suction value, is caused by the dry soil condition that triggered by field evaporation, even though it is under atmospheric pressure.

In terms of river embankment, the soil closest to the surface layer, which is located on the unsaturated soil zone, is always referred to problematic soil since various matric suction values can result in significantly varied soil shear strengths (Fredlund, D.G., 2006).

Based on the result, the varied matric suction distribution value is considered to cause the significant soil shear strength changing as well as change of the embankment stability. Therefore, in this research, the surface soil was thoroughly investigated.

4.2 Soil Characteristics of Embankment

Table 2 provides soil characteristics sampled on January 8, 2014. Based on the Unified Soil Classification System (USCS), the soil type is CL, inorganic clay and silt (fine-grained soil) with low plasticity. Furthermore, in terms of expansive soil characterization (Chen, 1988), the soil is classified as medium expansive characterization.

Table 2 River Embankment Soil Characteristics

Soil Characteristics	unit	Embankment
Specific gravity, G_s	-	2.65
Percentage of gravel	(%)	0
Percentage of sand	(%)	19.91
Percentage of silt	(%)	29.03
Percentage of clay	(%)	51.07
USCS classification	-	CL
Liquid limit, LL	(%)	47.32
Shrinkage limit, SL	(%)	11.73
Plastic limit, PL	(%)	23.40
Plasticity index, PI	(%)	23.92
Expansive soil characterization (Chen, 1988)	-	Medium

(observed data on January 8, 2014)

From the compaction test result, the relationship between the water content (w_c) and the dry unit weight (γ_d) of soil is presented in Figure 5. It could be seen from the standard Proctor compaction result (with compaction energy 594 kJ/m^3) that the initial compacted soil exhibited a double peak compaction curve.

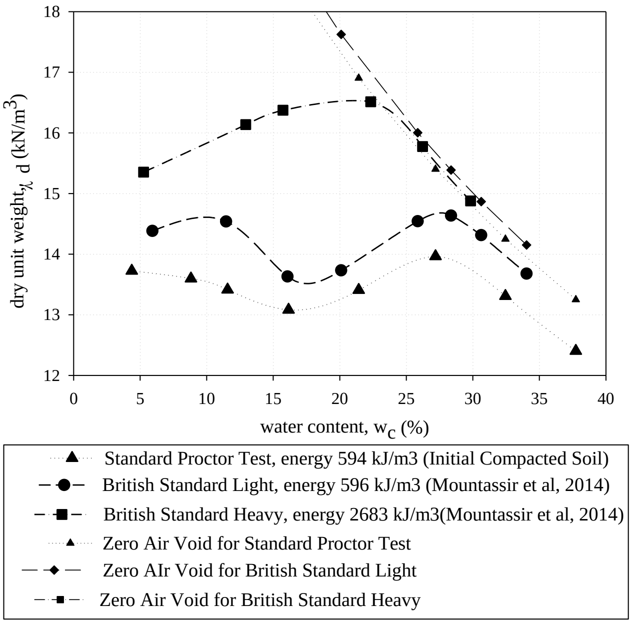


Figure 5 Compaction test results in three different compaction energies

In fact, similar compaction behavior was also encountered on river embankment soil that was investigated by Mountassir et al. (2014). In Figure 5, irregular double-peak compaction curves also existed on the soil that was compacted with a low compaction effort (British Standard Light, BSL with compaction energy 596 kJ/m^3), where two peaks occurred upon identical dry unit weight value. This generally means that when low compaction effort is applied, the dry unit weight might result in a different value owing to a slight change of water content. However, this double peak can be altered into a single peak if the soil is compacted with a high compaction effort (British Standard Heavy, BSH with compaction energy 2682 kJ/m^3), as shown in Figure 5.

In this research, the second peak of the compaction curve was selected as the initial compacted soil condition for the cyclic drying–wetting test. This selection was made owing to a greater dry unit weight value and was also based on the actual soil condition when it was initially used as river embankment material. The soil material was derived from a riverbed that possessed high water content and was composed of fine-grained soil. Based on these reasons, the maximum dry unit weight and optimum water content were 13.96 kN/m^3 (γ_d max) and 26 % (w_c opt).

The soil water characteristics curve of compacted soil is shown in Figure 6.

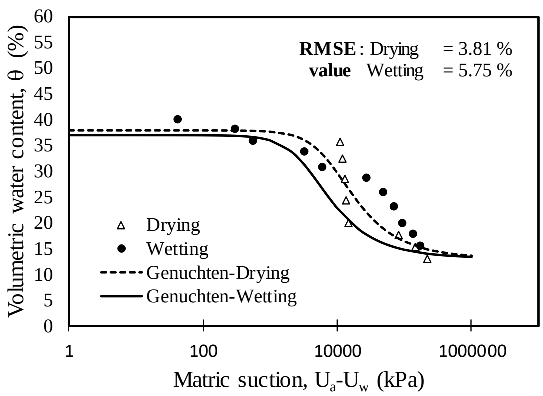


Figure 6 Soil water characteristics curve of compacted soil

The observed data (triangle shape-marked and solid circle-marked) are derived from 1st cycle of drying-wetting test of compacted soil at laboratory and the predicted data (solid line and dashed line) are estimated by using equation formulated by van Genuchten (1980).

4.3 In-Situ and Laboratory Investigation Result

4.3.1 In-Situ Investigation Result

Table 3 shows the result of the in-situ investigation during the season that was started from January 2014 to April 2014. In this area, various levels of rain intensity occurred where January 2014 was on the middle of the rainy season (151–200 mm) until the peak of the rainy season at the end of February 2014 and in the beginning of March 2014 (201–300 mm). Then, mid-month of March into April 2014 was on the dry season. The flow area of the river (m^2) is presented in Table 3 to better describe the river water level due to various rain intensities. A high value of flow area implies an increasing water level, and vice versa.

From Table 3, it can be concluded that if water level rises, the following soil properties will increase: water content (w_c), saturation degree (S_r), and void ratio (e). Meanwhile, the following soil properties will decrease: dry unit weight (γ_d), undrained cohesion (C_u) and matric suction (U_a-U_w) On the other hand, in terms of water content change during the investigation period, several data showed irregular behavior where it was not consistent with the flow area change. For example , data on January 29, 2014 and February 12, 2014 showed a low water content value, even though the flow area started to increase. This might be due to a technical problem where the soil sampling location had to be moved to another location owing to a shallow landslide occurrence. This particular circumstance might cause irregular behavior in water content change. In addition, in terms of suction value change during the investigation period, several data also showed irregular behavior. Even though the rainy season started in January 2014 and ended in mid-month of March 2014, data on January 29, 2014 and February 12, 2014 (low rainfall intensity) showed high suction value, while a low value was evident in the remaining data until April 2014. This might be induced by the suction value on surface soil that was susceptible to change due to evaporation upon low rainfall intensity; therefore, a high suction value occurred even in the rainy season. In addition, a low suction value during the dry season (middle of March until April 2014) occurred owing to the fine-grained behavior of silty clay soil. It has low permeability value which are 3.71 x 10^{-6} m/s (upper part) and 1.08 x 10^{-6} m/s (lower part). Therefore, it still retains water after the peak rainy season (high rainfall intensity) and even though the dry season had already started, the soil still contained lots of water and thus low suction was evident. The moisture retention capacity of the upper soil layer (clayey sand) is high and the permeability is low to avoid the high quantity of flow into the deeper layer depth (Thielen, A. and Springman, S.M., 2006). The varied soil suction distribution is caused by the evaporation effects, especially in the dry season (Kassim et al, 2012).

Table 3 Soil Property Results of the In-Situ Investigation during the Season

Soil Property		**Date of In-Situ Investigation**						
Item	Unit	15/01/2014	29/01/2014	12/02/2014	25/02/2014	11/03/2014	29/03/2014	15/4/2014
Rain intensity*	mm	151-200	151-200	151-200	151-200	201-300	201-300	201-300
Dry unit weight, γ_d	kN/m^3	13	14	13	12	12	11	11
Water content, w_c	%	25	27	26	36	35	29	36
Saturation degree, S_r	%	67	82	73	82	78	54	76
Void ratio, e	-	0.99	0.87	0.95	1.15	1.20	1.40	1.26
Undrained cohesion, c_u	kN/m^2	104	59	129	47	35	85	19
Suction, (U_a-U_w)	kN/m^2	40888	24672	143765	34	62	2966	9
Flow area, A	m^2	489	548.24	566.87	702.5	597	355.5	580

*data sourced from http://karangploso.jatim.bmkg.go.id (Indonesian Agency for Meteorological, Climatological and Geophysics)

4.3.2 Drying–Wetting Behavior in the Laboratory

4.3.2.1 Behavior of River Embankment Soil due to Drying and Wetting

Figure 7 illustrates the volume phase of clay soil after the drying and wetting process. It was mentioned in Table 2 that the river embankment soil is classified as inorganic clay and silt, with medium expansive characterization behavior. Furthermore, this behavior means that not only do soil particles have the ability to volumetrically increase or swell when adsorbing the water, but they also have the ability to volumetrically decrease or shrink when desorbing the water (Basma et al., 1996, Estabragh et al., 2015, Lin and Cerato, 2015).

During the wetting process of clay soil, as shown in Figure 7 (a), the water volume phase (V_w), volume of void (V_v), as well as the total volume of soil (V) increased to V_w*; V_v* and V*, respectively. The volume of air (V_a) was decreased into V_a*. However, the solid volume (V_s) was unchanged. Therefore, the void ratio increased and the dry unit weight decreased owing to these changes. This occurred due to the physicochemical factor of clay mineralogy (Seed et al., 1962). The surface structure of clay mineral has a characteristic to strongly attract water molecules. In addition, clay also has a negative electrical charge that always attracts cations for obtaining electrical neutrality in soil. Hence, owing to the hydrated water and attracted cations, there will be an imbalance in electrical charge that leads the soil particles to be apart each other.

Meanwhile, during the drying process of clay soil, as shown Figure 7 (b), the water volume phase (V_w), volume of void (V_v), as well as the total volume of soil (V) decreased to V_w*; V_v* and V*, respectively. The volume of air (V_a) was increased into V_a*. However, the solid volume phase (V_s) was unchanged throughout the experiment. Therefore, the void ratio decreased and the dry unit weight increased owing to these changes. The drying process could be analogized with the higher capillarity or high negative pore water pressure, which reduces the hydrostatic pressure. Therefore, the effective stress and soil shear strength increases. However, if the negative pore water pressure is more than the soil cohesion value, the soil cracks.

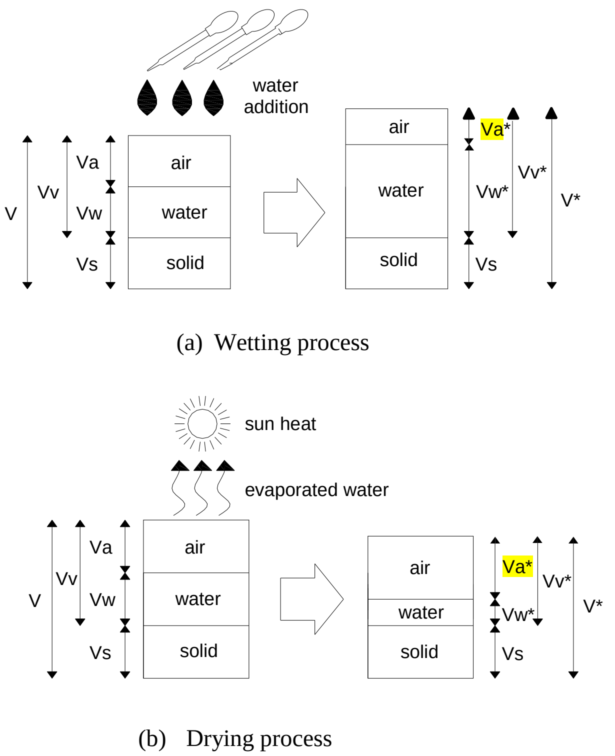


Figure 7 Soil volume phase illustration of clay soil due to wetting and drying (* = altered volume phase)

The drying and wetting of clay as fine-grained soil results in different behavior than the drying–wetting of coarse grained soil (sand or gravel), especially different total volume of soil. In coarse-grained soil, soil particles do not swell when they adsorb water or shrink when the water is desorbed. Therefore, the total volume of soil is unchanged. In sandy granular soil, the void ratio hardly changes upon drying process and a bit increase during wetting process (Eid et al., 2015).

4.3.2.2 Drying–Wetting Behavior of Dried–Wetted Soil in Each Cycle

The changes in soil properties during drying-wetting cycles are important and should be analyzed. Based on the previous discussion, the soil is classified as medium expansive characterization, which means that the volume change is susceptible to change due to the presence of water. Figure 8 shows the change of soil dry unit weight due to cyclic drying-wetting.

In all cycles, the soil dry unit weight gradually increases during drying process (upward arrow) and gradually decreases during the wetting process (downward arrow). It generally means that the total volume of soil increased during wetting process and it decreased during drying process. Based on research conducted by Osipov et al (1987), if the wetting process is applied to the dry clay, it induces an entrapped air that causes the high internal pressure as well as high total swelling of the soil. Hence, the soil dry unit weight is reduced during wetting process.

Owing to wetting in the 1st cycle, the soil dry unit weight decreased by approximately 22.49 %, from 15.56 kN/m^3 to 12.06 kN/m^3. Similarly, the soil dry unit weight decreased gradually by 21.48 %, from 14.62 kN/m^3 to 11.48 kN/m^3 in the wetting process of the 2nd cycle. However, it was slightly lower in rate of reduction than in 1st cycle. In the 3rd cycle, soil dry unit weight decreased gradually by approximately 17.36 %, from 14.46 kN/m^3 to 11.95 kN/m^3. This means that the rate of reduction was lower than in the 2nd cycle.

However, at the end of wetting process, the soil dry unit weight value decreased from 1st cycle to 2nd cycle, and then it increased in the 3rd cycle. These changes exhibit that the expansive characterization was proven from the 1st cycle to the 2nd cycle, but it was reduced in the 3rd cycle.

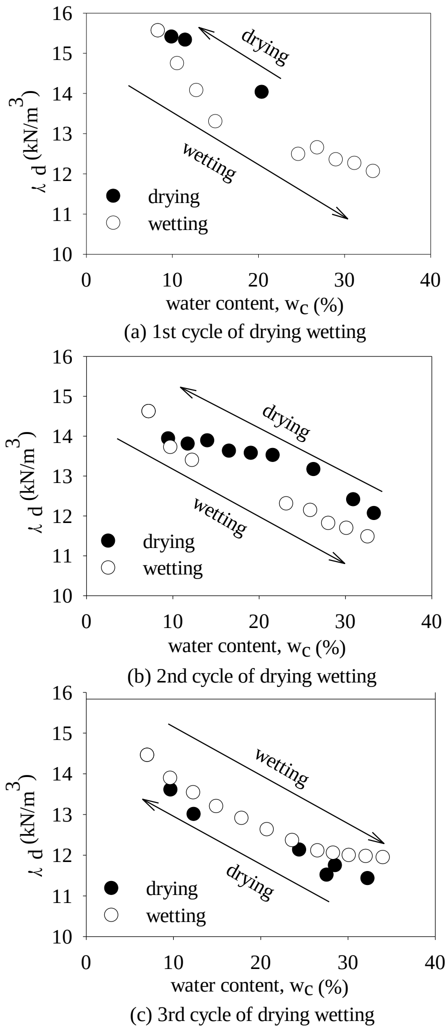


Figure 8 Comparison of water content (w_c) and dry unit weight (γ_d) due to cyclic drying-wetting

In terms of cyclic drying-wetting, Al-Homoud et al. (1995) revealed that if the soil is partially dried until achieving its initial water content, there will be reduction of swelling intensity due to the cycles. However, if the soil is fully dried until achieving its shrinkage limit value, the soil will experience incremental swelling due to the cycles. In this research, before conducting the wetting process, the soil had been dried until it reached 7.09 % (air-dry water content) which is far below even the shrinkage limit value, SL 11.73 %. Therefore, as the soil experienced a swelling increment due to the drying–wetting cycle, the soil dry unit weight was gradually reduced. From Figure 9, it can be concluded that hysteresis occurred as a result of the drying and wetting process. Moreover, the hysteresis was slightly to be started in the 1st cycle, it then reached the highest value in the 2nd cycle, and continuously decreased in the 3rd cycle. In term of saturation degree, hysteresis could also be seen from the suction value gaps at certain value of saturation degree particularly at 2nd cycle as shown in Figure 9.b. Hysteresis theoretically occurred because the soil could not attain the same suction value during the drying and wetting process.

Hysteresis of drying–wetting cycles is caused by several factors such as the ink bottle effect (Radcliffe, D.E. and Simunek, J. 2010). The ink bottle effect occurs when the soil does not have uniform pore size. Therefore, after draining the water through the small pores upon drying process, the water could not be able to drain into the same pore size at certain suction values upon wetting process. This is due to the difficulty of the water when trying to reach large soil pores during the wetting process.

In fact, the peak hysteresis increment in the 2nd cycle was consistent with the change of soil dry unit weight; it also reached the lowest value in 2nd cycle. In addition, the hysteresis reduction in the 3rd cycle induced the change of soil dry unit weight where it started to be increased in the 3rd cycle. From these occurrences, it seems that the expansive characterization has its influence on the soil dry unit weight change as well as on the hysteresis intensity.

4.3.3 Corresponding Soil Properties Between In-Situ Condition and Dried-Wetted Soil

In order to clarify the soil property changes, the results from the in-situ investigation and laboratory tests were compared. The corresponding soil properties among this comparison would be used to determine the number of required drying and wetting cycles for dried-wetted soil to exhibit similar behavior to that of the in-situ condition.

From this comparison, as much as four datasets correspond between in-situ soil and dried-wetted soil properties as it shown in Table 4.

Three in-situ data, which were investigated on January 15, February 25, and March 11, 2014, consecutively correspond with the wetting process at W4, W7 and W8 in 2nd cycle of dried–wetted soil. Meanwhile, one piece of in-situ data, which was investigated on April 15, 2014, corresponds with the drying process at D9 in 3rd cycle of the dried–wetted soil. Dry unit weight (γ_d), void ratio (e), and undrained cohesion (c_u) are the in-situ soil properties that have values identical to the dried-wetted soil. However, there are some soil properties that have different values, such as the water content (w_c), saturation degree (S_r) and matric suction (U_a-U_w). This might be due to the difference of absorbability and desorption ability between in-situ and dried-wetted soil. Generally, the in-situ condition has greater absorbability and desorption ability than dried-wetted soil that is modeled in the laboratory. Therefore, these in-situ soil properties were almost always higher than those of the dried-wetted soil. The corresponded soil properties between field and laboratory is shown in Figure 10.

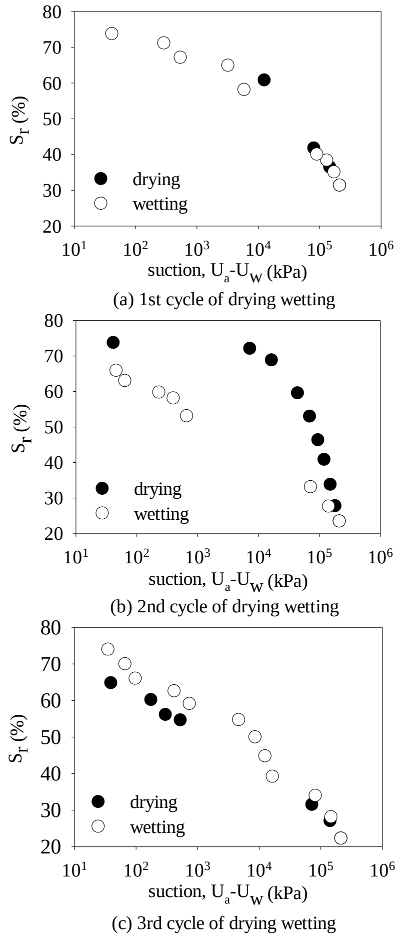


Figure 9 Comparison of suction (U_a-U_w) and saturation degree (S_r) due to cyclic drying-wetting

Table 4 Corresponding Soil Properties between In-Situ and Dried-Wetted Soil Condition

Date of observation		January 15, 2014		February 25, 2014		March 11, 2014		April 15, 2014	
Soil Condition		In-Situ	Dried-wetted	In-Situ	Dried-wetted	In-Situ	Dried-wetted	In-Situ	Dried-wetted
Step Series		-	W4 – 2nd cycle	-	W7 – 2nd cycle	-	W8 – 2nd cycle	-	D9 – 3rd cycle
Soil properties	Unit								
Dry unit weight, γ_d	kN/m^3	13	13	12	12	12	12	11	11
Void ratio, e	-	0.99	0.96	1.15	1.11	1.20	1.20	1.26	1.26
Undrained cohesion, c_u	kN/m^2	104	110	47	38	35	14	19	12
Water content, w_c	%	25	15	36	23	35	28	36	29
Saturation degree, S_r	%	67	41	82	55	78	62	76	62
Matric suction, (U_a-U_w)	kPa	40888	1456	34	663	62	231	9.4	50
Flow area, A	m^2	489	-	702.5	-	597	-	580	-

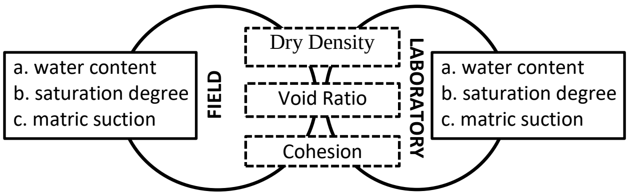


Figure 10 Corresponded soil properties

The results show that the dried–wetted soil requires 2 to 3 cycles to behave like in-situ soil. Or in another meaning, the in-situ soil had already experienced 2 to 3 cycles of drying–wetting since it was initially constructed. As the number of cycles referred to the number of the years that have passed, this generally means that in-situ soil had already experienced dry and rainy seasons for 2 to 3 years.

Based on this number of passed years, as the in-situ investigation was started in 2014, we can determine that the construction of the initial compacted soil had been performed at the end of 2011.

4.3.3.1 Time Ratio

To clarify the rate of soil property changes after being subjected to the drying and wetting process from its initial compacted condition, matter of time is necessary to compare between laboratory and in-situ investigation test. To solve this matter, a time ratio is proposed to synchronize the elapsed time period which the soil was dried and wetted in the laboratory and elapsed time period which the in-situ soil was dried and wetted in the field. This information is then used to trace back the real construction time of river embankment. For this purpose, the corresponding soil properties between in-situ and dried-wetted soil are used to determine the time ratio. In addition, the time difference of in-situ soil at each investigations and time difference of laboratory dried-wetted soil at each step are required. Furthermore, the proposed time ratio (t_r), as shown in Eq. (1), is ratio between elapsed time in field (t_{field}) and elapsed time in the laboratory ($t_{laboratory}$), as shown below:

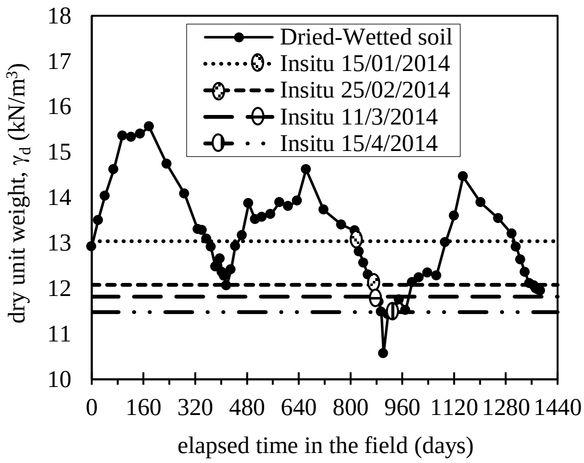
$$t_r = \frac{t_{field}}{t_{laboratory}} \qquad (1)$$

For example, two in-situ soil properties investigated on January 15 and February 25, 2014 which correspond with two laboratory dried-wetted soil properties at W4-2nd cycle and W7-2nd cycle. The in-situ time difference between them (t_{field}) is 41 days, and the laboratory dried-wetted time difference ($t_{laboratory}$) is 9 hours. Hence, the time ratio (t_r) is 109.33. This time ratio value means that if one day is needed as elapsed time in the laboratory, it will be equal to 109.33 days needed as elapsed time in the field (in-situ).

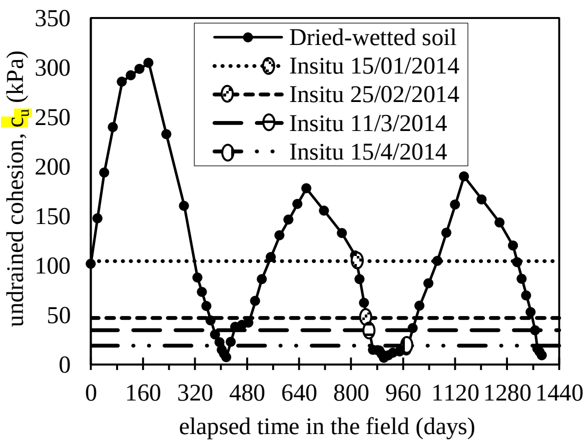
4.3.3.2 Comparison Curve

Based on the discussion in section 4.3.3., there are strong relations between laboratory and field data. To reveal this relation, time ratio is used for representing the time consideration of the soil property changes for both in-situ and laboratory conditions. Based on this ratio, the comparison curve is plotted as a function of time (days), which describes elapsed time in the field (in-situ condition).

Figure 11 shows the comparison between physical (dry unit weight, γ_d) and mechanical soil property (undrained cohesion, c_u) changes of dried-wetted soil due to the cycles, as well as the in-situ soil properties investigation result. Undrained cohesion (c_u) decreases within successive drying wetting cycles at laboratory. Similar to the research investigated by Wright, S.G. and Rogers, L.E. (1986), it reveals that there is reduction of cohesion of compacted highly plastic embankment's clay due to cyclic drying wetting. In addition, it could be summarized that the dry unit weight (γ_d) and undrained cohesion (c_u) are likely to be constant after experiencing the 3rd cycle of drying wetting process. Based on the diatomaceous mudstone investigated by Maekawa and Miyakita (1991), the soil strength property starts to be reduced after experiencing certain cycle of drying wetting process.



(a) Dry unit weight comparison



(a) Undrained cohesion comparison

Figure 11 Comparison of soil property between dried-wetted soil and in-situ soil conditions

In addition, from Figure 11, it could be seen that four in-situ investigation results were in good agreement with laboratory dried-wetted soil, as discussed in section 4.3.3. Corresponding data, marked with circles, were the in-situ investigations that were performed on January 15, 2014; February 25, 2014; March 11, 2014; and April 15, 2014. Meanwhile, the in-situ soil property investigations that existed in between those corresponding data points (January 29, 2014; February 12, 2014; and March 29, 2014), did not correspond with the dried-wetted soil properties. This might be caused by a river water fluctuation that was not always in sequence where the water level during investigations even decreased in the rainy season or even increased in the dry season. According to the research investigated by Duong et al. (2014) that monitored river water level during the flood seasons, the river water level experienced several cycles of rises and falls although it is still in the same flooding period.

Eventually, the four datasets were selected as corresponding data between dried–wetted soil and in-situ soil. To better understand the importance of the time ratio, the relationship between drying–wetting behavior at the laboratory (dried-wetted soil) and at the field (in-situ soil) needs to be analyzed.

4.3.3.2.1 Relation between Drying–Wetting Behavior at Laboratory Dried-Wetted Soil and In-Situ Soil.

Regarding the discussion in section 4.3.2.2., in the 2nd cycle of the wetting process, the lowest value of soil dry unit weight was reached. This condition is in accordance with the in-situ investigation data on March 11, 2014 where there was shallow slip failure occurred in the field, as shown in Figure 2.c. The failure might be caused by the reduction of soil dry unit weight during the 2nd cycle of the wetting process. It generally means the peak properties change that occurs in the alteration from 1st cycle into 2nd cycle of drying wetting process at laboratory could be coincidentally related with the failure of the embankment.

In addition, to clarify the rate of soil property change, time ratio is used to trace back the construction time of river embankment. The calculation is based on the total elapsed time of three drying–wetting cycles in the laboratory which needs 12.7 days.

Using this total elapsed time in laboratory, the total elapsed time in the field is calculated by using previous calculated time ratio (t_r = 109.33). Thus, the calculated total elapsed time duration in the field is ±1388 days.

By tracing back the time from this information, month of October 2011 had been predicted as the time when the river embankment was initially constructed. The Ministry of Public Works and Housing has also stated that the embankment was indeed constructed in the end of 2011.

5. CONCLUSIONS

This paper clarified the change as well as the rate of change, of physical and mechanical properties of the river embankment at research observation site in the Bengawan Solo river. This was accomplished by conducting an in-situ investigation and laboratory tests. The major conclusions can be summarized as follows:

1) For the characterization of basic soil properties, the initial compacted soil was tested using a standard Proctor compaction test; the soil exhibited a double peak compaction curve due to low compaction effort, where two peaks occurred with identical dry unit weight value. These peaks could be altered into single peak compaction if the compaction effort was higher. In addition, owing to the fact that the soil has medium expansive characterization, the soil particles easily swell when adsorbing the water and shrink when desorbing the water.
2) Irregular behavior was observed in the in-situ investigation results where low suction value and high value of water content occurred during the dry season. This was due to the inorganic clays and silts (according to USCS classification) behavior as fine-grained soil, which causes the soil to retain the water after experiencing the rainy season.
3) For the clarification of the soil property changes, it was concluded that the in-situ soil condition had already encountered dry and rainy seasons for 3 years.
4) As a comparison to the field condition, during the 2nd cycle of the wetting process in the laboratory, the soil dry unit weight reached the lowest value, which is the same as the in-situ condition that also had problem in shallow slip failure on March 11, 2014. There is strong relation upon peak properties change in the laboratory and failure at in-situ.
5) To clarify the change rate of soil properties, the time ratio was proposed. Furthermore, the elapsed time between in-situ investigation in the field and the drying-wetting process in the laboratory could be synchronized respectively using the time ratio. Based on the synchronization, October 2011 is predicted as the time when the river embankment had been initially constructed.

As a general research objective, an information regarding soil properties change in time function during drying-wetting cycles could be used to predict the soil properties in the future. This means that the river embankment stability could be predicted as well.

6. ACKNOWLEDGEMENT

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