Soil Shrinkage and Consolidation Study on Flood Embankments in Swamp irrigation Areas (Case Study: Tulang Bawang - Indonesia)

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Abstract Research in this paper discusses shrinking and consolidation of flood embankments soil in swamp irrigation areas. The flood embankments are made from swampy soil materials. The focus of this research is the reduction of dyke embankment height that occurs due to soil shrinkage and soil consolidation. Investigations about the time of consolidation and land subsidence that occurred on the embankment at certain periods after the embankment established were also carried out in this study. The research sites are some swamp irrigation areas in the Tulang Bawang Watershed, around North-East Lampung, Indonesia. This research was carried out by conducting laboratory tests on soil samples and field observations on the reduction in height on flood embankments in the study area. The research shows that the main cause of total decrease on the embankment is due to linear shrinkage, consolidation of soil under the embankment, an immediate subsidence, and the subsidence of the embankment themselves. Their contribution to total decrease of embankment is 42.51%, 34.48%, 18.32%, and 4.62%, respectively. Results also indicate that the ratio between the percentages of embankment consolidation in downstream area happens faster than the one in upstream area of the river.

Keywords Shrinkage, Consolidation, Embankment, Swamp Irrigation

1. Introduction

Flood embankments on swamp irrigation are made by utilizing local soil by digging the soil on the right and left of the plan of the dike wall. This utilization of local soil is carried out in consideration of cost efficiency and easy access to material and technical implementation of the work [1]. On the other hand, flood protection dykes in swamp irrigation areas requires special attention in relation to the decline or depreciation that will be experienced. Scientifically, the decline of flood embankment body due to the material forming it, was rarely discussed by the public. Basically, if the reduction or depreciation is well considered in the design of the embankment, there will be cost savings in the construction process. Studies investigating the behavior of soil depreciation on flood embankments in swamp irrigation are an interesting special topic. Depreciation that occurs on expansive or soft soils that form dikes will cause a decrease in the embankment body [2]. Furthermore, the burden on the embankment will also cause a decrease in the embankment body due to consolidation on the embankment body itself and consolidation on the soil under the embankment. On the other hand, it is also necessary to consider an immediate settlement that occurs in the soil under the embankment. In addition, Kumor [3] found that the main problem in the application of geotechnique in the field was estimating depreciation due to post-consolidation on expansive soils.

On the other hand, [4] who evaluates the volume depreciation in relation to changes in water content, suggests that the water content must also be considered together with the nature of the soil material in the volume depreciation. In principle, the shrinkage limit is defined as a condition where the land mass does not change in volume when the water content decreases [5]. For this reason, we need to know the volumetric shrinkage value (V_c) of the soil. V_c is the change in soil volume from initial volume until the soil no longer experiences shrinkage in the elongated direction.

In relation to the reduction, we also need to determine the linear shrinkage (L_s), which is the decrease of soil which can occur due to the loading on it. This decrease is caused by elastic deformation of the soil in dry, wet or saturated soil conditions where the decrease does not occur with changes in water content. The magnitude of this reduction will depend on the shape and dimensions of the foundation and the type of material in which the foundation is placed [6]. In addition to the elastic deformation of the soil, the addition of a load over the surface can also cause the soil layer underneath to compress due to the release of water or air from the pore, which is called consolidation. The decline in the flood embankment will run over time. A decrease due to shrinkage (linear shrinkage) and an immediate settlement due to elastic deformation of the soil can be assumed to occur immediately. However, it needs to be examined specifically regarding the time of depreciation and the time of immediate settlement.

The research in this paper discusses the shrinking and decreasing behavior of the soil on flood dyke embankments which were made from swampy soils in swamp irrigation areas. The focus of this research is the reduction of dyke embankment height that occurs due to soil shrinkage and soil consolidation. Investigations about the time of consolidation and soil subsidence that occurred at certain periods after the embankment established were also carried out in this study. The research sites are some swamp irrigation areas in the Tulang Bawang Watershed, around North-East Lampung, Indonesia.

2. Materials and Methods

The soil sample used in this study is swamp soil that exists between Tulang Bawang River and Pidada River, Tulang Bawang Regency. Three soil sampling and observations were carried out at 3 places located within the scope of the Pidada River Basin. They are Aji Mesir, Batu Ampar and Rawa Ragil points. While other samples were taken at the Sumber Sari and Gedung Jaya locations, which take place within the scope of the Tulang Bawang River Basin.
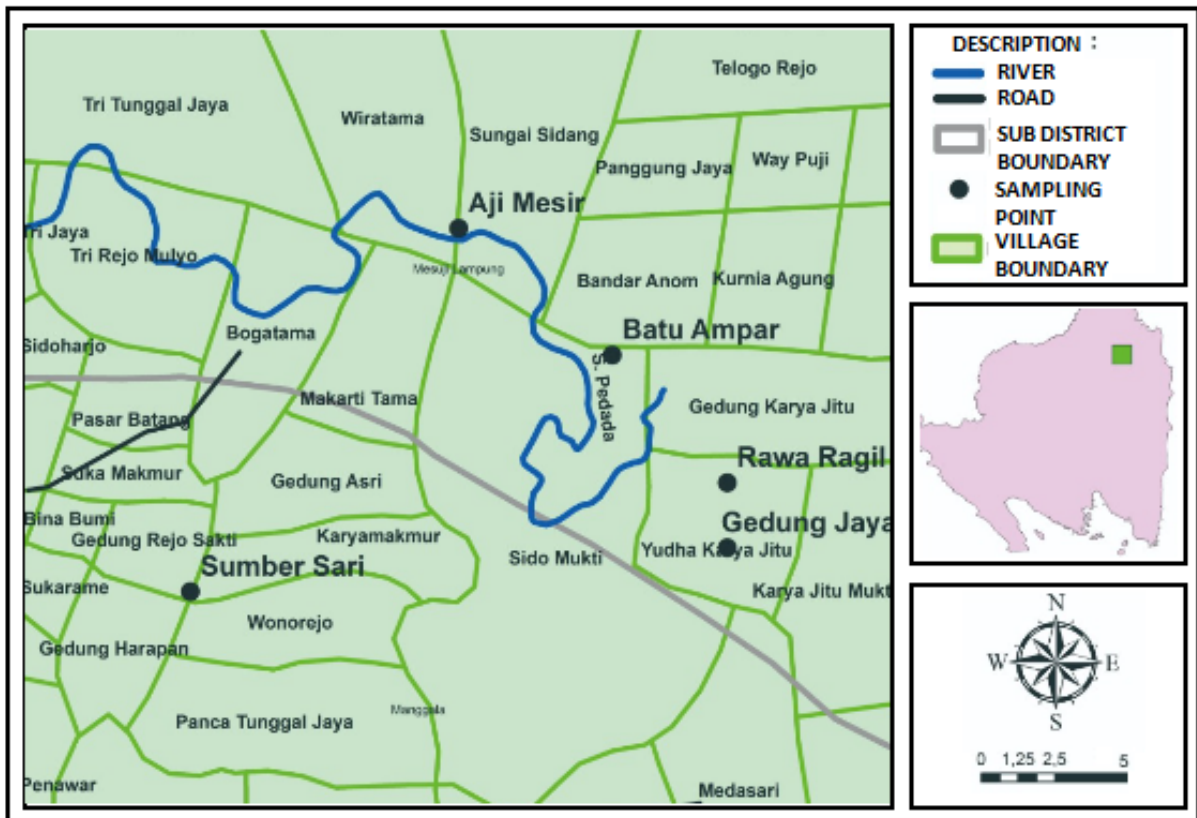

Figure 1. Study area [7]

This research was carried out by conducting laboratory tests on soil samples and field observations on the reduction in height on flood embankments in the study area. The reduction in the height of the flood embankment to be reviewed is the settlement assumed to be caused by soil shrinkage, immediate decrease and decrease due to primary consolidation. The depth of soft soil around the study site was estimated using Cone Penetration Test. The steps undertaken to analyze the reduction in flood embankments and the time of decline are as follows:

2.1. Calculation of Decrease due to Linear Shrinkage

Decrease in height of embankments due to linear shrinkage can be predicted by calculating the volumetric shrinkage by conducting shrinkage and moisture content tests. Following are some of the equations used in determining the shrinkage limit, volumetric shrinkage, shrinkage ratio and linear shrinkage.

2.1.1. Shrinkage Limit Calculation

$$Ws = W - \frac{(V - V_d)\gamma_w}{W_d} \times 100\% \qquad (1)$$

with,
  Ws = shrinkage limit
  W = the weight of the wet ground
  V = volume of wet soil
  V_d = dry soil volume
  γ_w = unit weight of water content (kg/m^3)
  W_d = weight of dry soil

2.1.2. Volumetric Shrinkage Calculation

$$V_c = (w_0 - w_s) \times \frac{W_d}{V_d \cdot \gamma_w} \qquad (2)$$

with,
  V_c = volumetric shrinkage
  w_0 = initial water content
  w_s = shrinkage limit
  W_d = weight of dry soil
  V_d = dry soil volume
  γ_w = unit weight of water content

2.1.3. Linear Shrinkage Calculation

$$L_s = 100 \times \left(1 - \left[\frac{(100)}{(V_c + 100)}\right]^3\right) \qquad (3)$$

with,
  Ls = linear shrinkage
  Vc = volumetric shrinkage

2.1.4. Shrinkage Ratio Calculation

$$R = \frac{V_c}{w_0 - w_s} \qquad (4)$$

with,
  R = shrinkage Ratio
  V_c = volumetric Shrinkage
  w_0 = initial water content
  w_s = shrinkage limit

2.2. Calculation of Decrease due to Linear Shrinkage

$$Si = P.B.\frac{1-\mu^2}{E}.Ip \qquad (5)$$

with,
  S_i = immediate decline
  PI = evenly distributed load
  B = foundation width
  IP = influence factor
  μ = Poisson ratio
  E = Young modulus

2.3. Soil Subsidence as a Result of Consolidation

Pre consolidation pressure is the maximum overburden pressure that has ever occurred on the soil under test. If the OCR value <1, then the land has consolidated (decreased). The OCR value is the ratio between the pre-consolidation pressure and the current overburden pressure. To calculate the decrease due to this consolidation, we need to determine the work load, which is the flood embankment load and the soft soil load reviewed. In addition, the pore number (e_0) and compression index (C_c). In general, the amount of consolidation that occurs is as follows:

$$S = \frac{HC_c}{1+e_0}\log\frac{p_1'}{p_0} \qquad (6)$$

with,
  S = soil subsidence due to consolidation (cm)
  H = depth/height of land (cm)
  e_0 = initial pore number
  C_c = compression index
  p_1' = preconsolidation pressure = $p_0 + \Delta p$
  p_0 = effective overburden pressure before loading

2.4. Time of Consolidation

At the end of the consolidation, the land was considered to have reached the degree of consolidation of U90% with a T_v time factor of 0.848. This is because, after the primary consolidation, there is actually still a decline up to U100% with a T_V value of infinite ($\approx$). Time of consolidation can be determined based on the following equation:

$$t = \frac{T_v.H_{dr}^3}{C_v} \qquad (7)$$

with,
  t = consolidation time (seconds)
  T_v = time factor
  H_{dr} = depth of soil under consideration for consolidation (cm)
  C_v = consolidation coefficient

3. Results and discussions

In this study, the results and discussion are a combination of laboratory test data, field measurements, calculation results and analysis, which consist of:

3.1. Soil Type, Physical Properties, Clay Content, and Organic Content

Based on the USCS Method, 3 samples were of type SC (sandy loam) and CH (loam with high plasticity). Whereas based on the USDA [8] method, the samples are clay type. The clay content is between 36.44% - 79.94%. The more downstream of the sample location the clay content of the sample tends to be greater. Organic content of the samples ranged from 11.38% - 22.43% and was classified as clay or soft soils [9].

Table 1. Soil type, physical properties, clay content, and organic content

| Physical properties	Aji Mesir	Sumber Sari	Gedung Jaya	Rawa Ragil	Batu Ampar
Specific weight (Gs)	2.68	2.52	2.43	2.43	2.29
Unit weight volume (gr/cm³)	1.60	1.39	1.31	1.32	1.35
Mass density (gr/cm³)	1.61	1.35	1.32	1.37	1.40
Pore number ('e)	1.27	1.45	2.05	1.65	2.47
Degree of saturation (%)	85.90	70.63	83.59	73.70	104.87
Water content (%)	40.75	40.64	70.44	50.08	113.43
Porosity (%)	57.68	60.79	68.48	63.77	72.34
Silty clay (%)	36.44	46.53	47.69	53.97	79.94

3.2. Soil Settlement

To determine the amount of settlement and decrease due to shrinkage, we need to do a shrinkage test. Volume changes due to shrinkage can be seen on the basis of volumetric shrinkage, shrinkage ratio, and linear shrinkage. Calculation of settlement of soil can be seen in the table below.

Table 2. Results of calculation of soil settlement

Physical properties	Aji Mesir	Sumber Sari	Gedung Jaya	Rawa Ragil	Batu Ampar
Specific weight (Gs)	2.68	2.52	2.43	2.43	2.29
Unit weight volume (gr/cm³)	1.60	1.39	1.31	1.32	1.35
Mass density (gr/cm³)	1.61	1.35	1.32	1.37	1.40
Pore number ('e)	1.27	1.45	2.05	1.65	2.47

Based on Table 2, it appears that the average volumetric shrinkage value of the sample is above 66.3%. This is a significant change in soil volume compared to clay soils such as glacial fill, alluvial soil and Mio pliocene clays. The amount of linear shrinkage ranges from 16.36% - 19.08%. With this range of linear shrinkage values, all samples can be considered nearly uniform with the SC and CH soil classifications. This linear shrinkage will later be used to determine the magnitude of the flood embankment reduction. The magnitude of the ratio between volumetric shrinkage and the range of the initial water content to the water level of the shrinking limit (shrinkage ratio) has values ranging from 0.85 to 1.37. The relationship of the magnitude of changes in this volume to the range of initial water content to the level of water shrinkage forming a regression equation for volumetric losses, namely $YV = 27.144 \cdot \ln(X) - 37.534$, with a value of $R^2 = 0.9783$. Another equation that is formed is for linear shrinkage, namely $YL = 4.1918 \cdot \ln(X) - 0.3953$ with a value of $R^2 = 0.9743$. X itself is the range of initial water content to the limit of water content of shrinkage. In the form of a graph, the relationship is explained in the figure below.
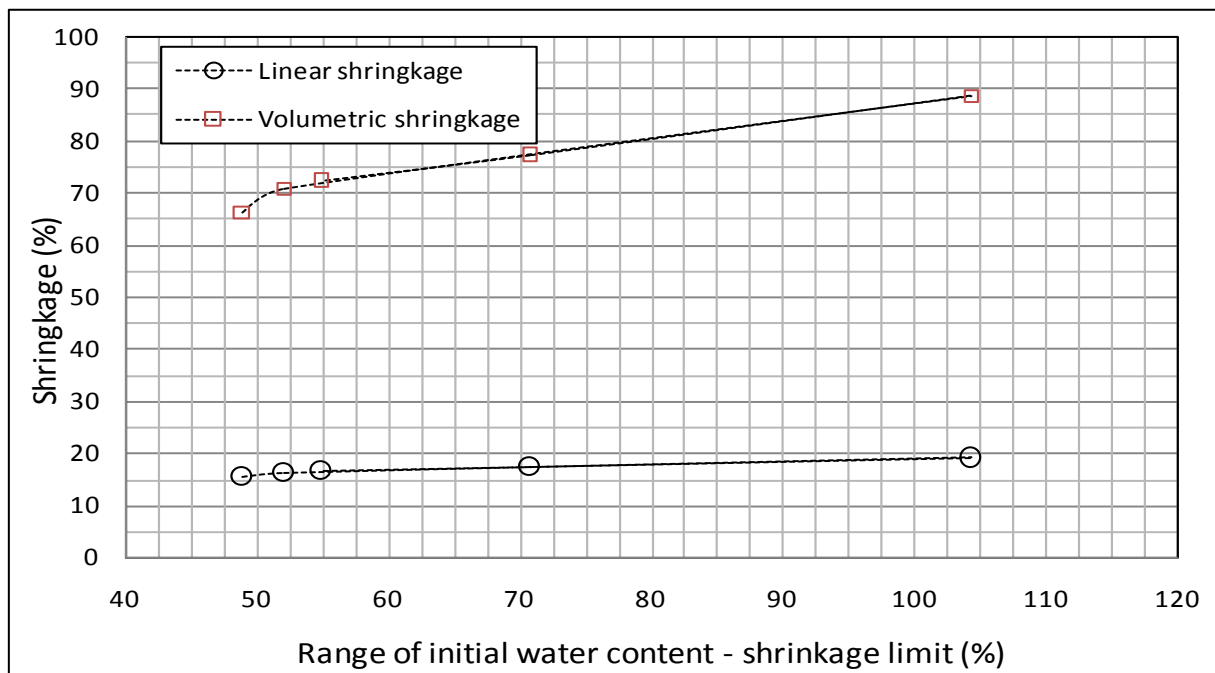
Figure 2. Shrinkage Vs range of initial water content - shrinkage limit

Based on the graph above, it can be seen that the relationship between the change in linear shrinkage volume and the range of initial water content to the shrinkage limit gives a lower value compared to the relationship of the volumetric shrinkage change, which is around 20%. This is because the linear shrinkage observed is only a change in one dimension that is only in the elongated direction.

3.3. The Settlement of Flood Embankment

The settlement that occurs due to linear shrinkage is obtained by multiplying the magnitude of the linear shrinkage to the initial embankment height for which data are obtained from the Public Works and Spatial Planning Office of Tulang Bawang Regency.

An immediate settlement, as in Equation 5 above, is obtained by multiplying the load, foundation width, Poisson number, foundation influence factor and divided by the young modulus value. Load evenly distributed is obtained by multiplying the volume unit weight by the height of the embankment.

In the consolidation test, the OCR value <1 means that both the embankment and the soil under the embankment experienced a decrease in consolidation. The magnitude of settlement is caused by consolidation on the embankment using Equation 6.

The value of soil consolidation under the embankment can be determined based on equation 7, and the results are presented in Table 6.

Table 3. The calculation of settlement of embankment due to linear shrinkage

Sampling location	Initial embankment height (cm)	Linear shrinkage (%)	The settlement due to linear shrinkage (cm)	Embankment height due to linear shrinkage (cm)
Aji Mesir	150	15.59	23.39	126.62
Sumber Sari	350	16.36	57.26	292.74
Gedung Jaya	350	19.08	66.77	283.23
Rawa Ragil	200	17.37	34.73	165.27
Batu Ampar	180	16.58	29.85	150.15

Table 4. The calculation of immediate settlement

Sampling location	Evenly distributed load (P) (gr/cm^2)	Foundation width (B) (cm)	Ip	Poisson number (μ)	Young Modulus (E) (gr/cm^2)	Immediate settlement (cm)
Aji Mesir	107.78	650	2.28	0.20	38,146.97	8.93
Sumber Sari	217.35	1,050	2.36	0.20	38,146.97	13.6
Gedung Jaya	213.68	1,050	2.36	0.20	38,146.97	13.3
Rawa Ragil	123.50	750	2.78	0.20	38,146.97	6.5
Batu Ampar	106.83	710	2.63	0.20	38,146.97	5.0

Table 5. Calculation of consolidation on embankments

Sampling location	Initial embankment height (cm)	Initial pore value (e_0)	Pore value due to embankment load (e_1)	Δe	Settlement on embankments due to consolidation (cm)
Aji Mesir	150	2.29	2.27	0.02	0.77
Sumber Sari	350	2.57	2.44	0.13	12.89
Gedung Jaya	350	2.74	2.62	0.12	11.21
Rawa Ragil	200	2.39	2.36	0.03	1.62
Batu Ampar	180	2.46	2.44	0.02	1.04

Table 6. The settlement due to consolidation of soils under the embankments

Sampling location	The height of soft soil (H) in cm	Load of embankment (ΔP) in gr/cm^2	Load of soil under the embankment (P_0) in (gr/cm^2)	(C_c)	(e_0)	Consolidation on the soil under the embankment (cm)
Aji Mesir	1.080	240	398.93	0.14	1.27	16.54
Sumber Sari	1.140	486	356.22	0.08	1.45	9.04
Rawa Ragil	1.820	264	490.37	0.17	1.65	40.23
Batu Ampar	1.840	243	341.22	0.36	2.47	44.33

If the total settlement due to linear shrinkage, immediate settlement and consolidation, compared to the settlement that occurred on the embankment in the field, there will be a uniform difference as in Table 7. This means that the results of the calculation of the settlement of embankment in the study area can be said to be close to the truth. (Quite different results were produced by sampling from Gedung Jaya. Therefore the calculation for the Gedung Jaya sample is not continued because it is considered as invalid data).
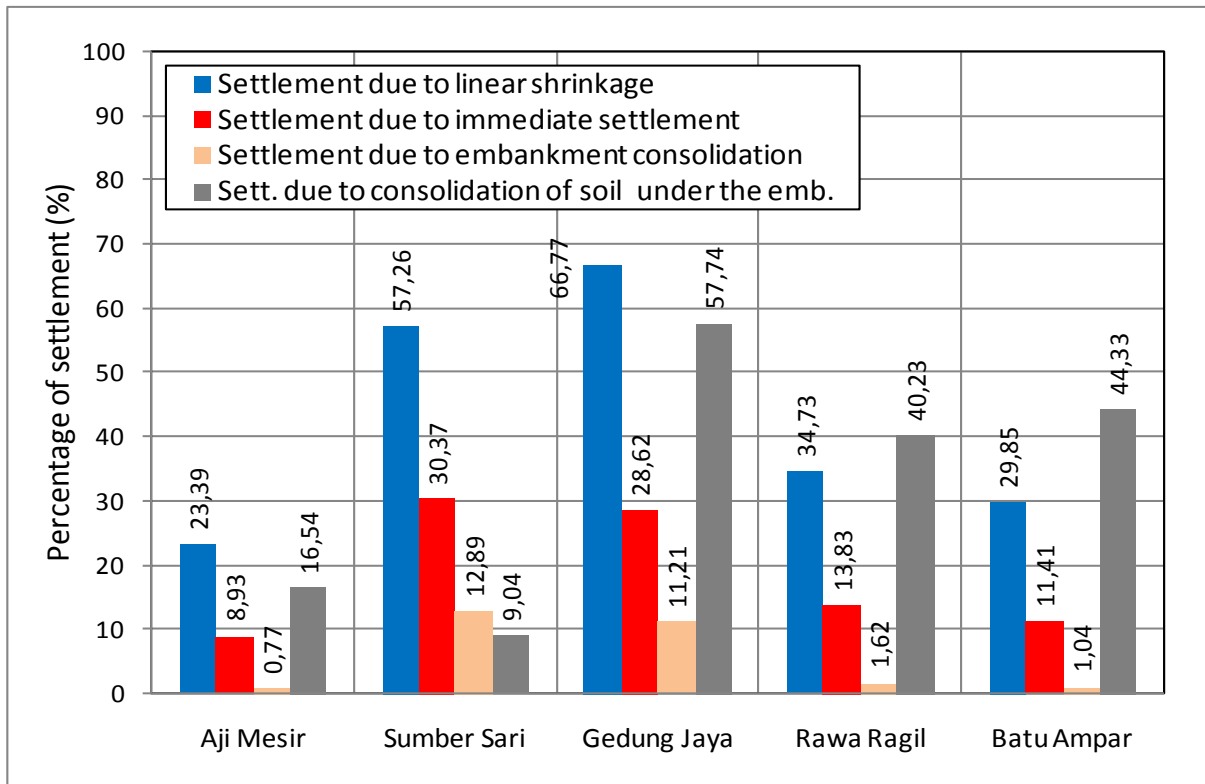
Figure 3 illustrate the contribution of each settlement in each sampling location.

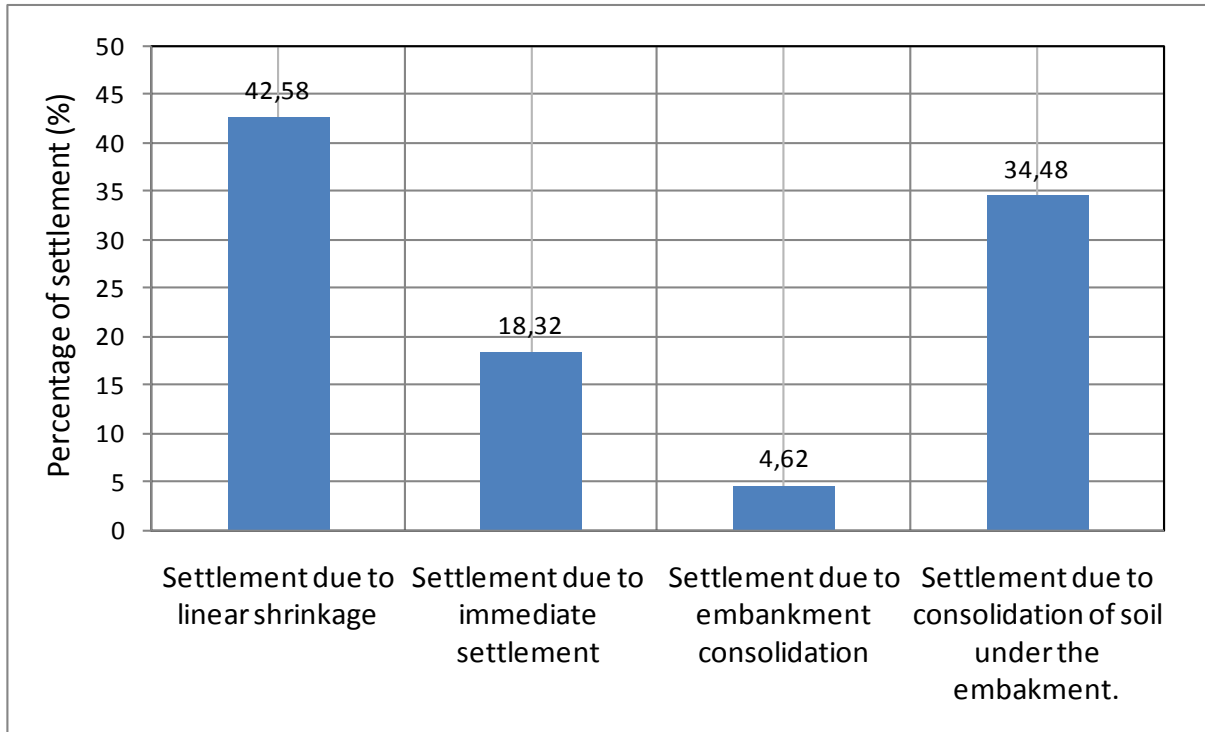The contribution of each type of settlement to the total embankment settlement is presented in Figure 5. The figure shows that the main cause of total settlement in the embankment is the settlement due to linear shrinkage. It contributes around 42.51% of total settlement. The next cause of the dike reduction is the consolidation of soil under the embankment, which contributes of 34.48% of total settlement. Furthermore, the cause of the settlement in the embankment was an immediate settlement which contributes around 18.32% of total settlement. The type of settlement that contributes the smallest to the total settlement of the embankment was the settlement of the embankment themselves, which was around 4.62% of total settlement.

Table 7. Difference of theoretical embankment height and real embankment height (field measurements)

Sampling location	Initial height of embankment (cm)	Height of embankment after consolidation (cm)	Theoretical height of embankment after consolidation (cm)	Δ
Aji Mesir	150	95	100.38	5.66%
Sumber Sari	350	260	240.44	7.52%
Rawa Ragil	200	115	109.59	4.70%
Batu Ampar	180	90	93.38	3.75%

Figure 3. Contribution of each settlement to the total settlement in each sampling point

Figure 4. Contribution of each type of settlement to the total settlement

Table 8. Consolidation Time values based on the calculation

Sampling location	Embankment			Soil under the embankment		
	Embankment height (cm)	Consolidation (cm)	Time (month)	The depth of soft soil (cm)	Consolidation (cm)	Time (month)
Aji Mesir	150	0.77	1.30	1,080	16.54	22.45
Sumber Sari	350	12.89	1.82	1,140	9.04	5.25
Rawa Ragil	350	1.62	0.58	1,980	40.23	12.04
Batu Ampar	200	1.04	1.12	1,820	44.33	29.15

Table 9. Consolidation Time values based on the calculation

Sampling location	Existing embankment height (cm)	Theoretical embankment height (cm)	Δ (%)	The time needed for consolidation (observations) (month)	The time needed for consolidation (calculation) (month)	Consolidation time T90
Aji Mesir	127.32	132.70	4.22%	67	22.45	Reached
Sumber Sari	347.63	328.07	5.63%	44	5.25	Reached
Rawa Ragil	163.56	158.15	3.31%	40	12.04	Reached
Batu Ampar	131.25	134.63	2.57%	17	29.15	Unreached

3.4. The Settlement of Flood Embankment

The time of consolidation is the time required for the soil to become compressed by removing the soil pore water due to loading. The time of consolidation of the embankment and the underlying soil is calculated based on equation 7 and is presented in Table 8. Based on Table 8, it can be seen that the consolidation time occurring on the embankment is much shorter, which ranges from 0.58 to 1.82 months, when compared to the consolidation time on land under the embankment, which is between 5.25 and 29.15 months. This may occur due to the height of the embankment layer is shorter when compared to the one of the underlying soil layers.

In order to find out whether the current dike has reached its consolidation time, we need to compare the time span since the dike was made with its consolidation time. Based on Table 9, it appears that the consolidation process has

been completed on the embankment Aji Mesir, Sumber Sari, and Rawa Ragil. On the other hand, the consolidation process at the Batu Ampar embankment is still in process.

A decrease in embankment due to linear shrinkage and an immediate decrease are assumed to occur simultaneously and occur immediately since the embankment was made. Whereas the decrease of embankment and the soil under the embankment due to its consolidation will follow the time of its consolidation, although actually the soil will continue to become incompressible in its secondary consolidation which is smaller and slower, until it reaches plastic deformation of soil particles. The ratio between the percentage of embankment reduction and time in the Rawa Ragil and Batu Ampar areas is greater than the one in Aji Mesir and Sumber Sari. This might have happened because Rawa Ragil and Batu Ampar are located in the downstream area which has deeper soft soil layers, which is between 1.82 to 1.84 m. While Aji Mesir Aji Region and Sumber Sari are located in the upper reaches of the river which has a depth of soft soil layers between 1.08 to 1.14 meters. This condition results in two types of curve of ratio between the percentage of embankment reduction and time, for sampling locations in the upstream and downstream area of the river as illustrated in Figure 5. The curves are produced by regression equation as follows:

$Y_1 = 0,0163. \ln(x) + 0,2703$ for upstream area

$Y_2 = 0,0512. \ln(x) + 0,2987$ for downstream area

with,

Y_1: ratio between existing height of embankment to the initial height of embankment for area located in upstream of the river (%).

Y_2: ratio between existing height of embankment to the initial height of embankment for area located in upstream of the river (%).
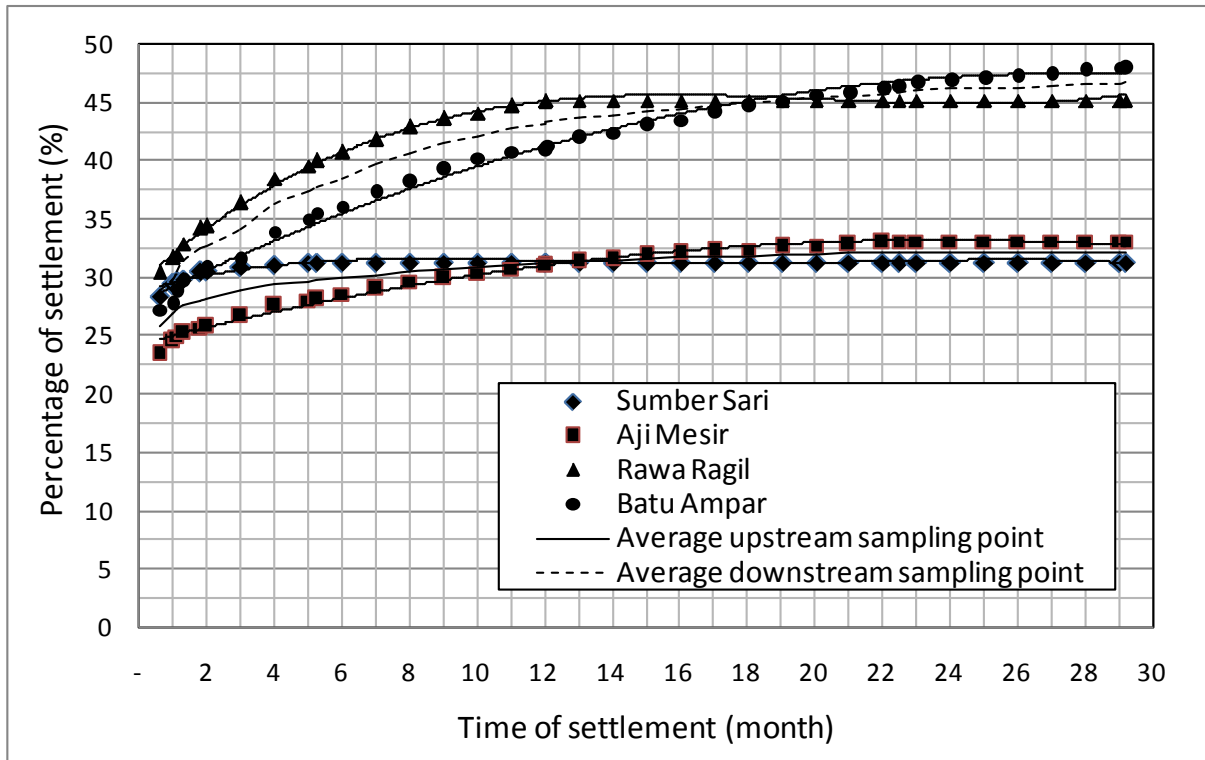
X: time of consolidation (month)

Figure 5. Relationship of the percentage of settlement and time

4. Conclusions

Case studies of embankment decline in swampy areas due to shrinkage and consolidation in the Tulang Bawang watershed have been investigated and analyzed. The study provides the following conclusions:

1. Linear shrinkage contributes between 16.36% - 19.08% of the total decrease. This range of linear shrinkage occurs in all types of soil. The value of reduction based on calculations due to linear shrinkage in embankment samples in the field ranged from 23.39 - 66.77 cm.

2. The relationship between changes in the linear direction (YL) with the difference between the water content of the shrinkage limit and the initial water content (X) forms a regression equation $YL = 4.1918 . \ln (X) - 0.3953$ with a value of $R^2 = 0.9743$.

3. Linear shrinkage gives the biggest contribution in decreasing total embankment. Next in a row, from large to small, is the consolidation of land under the embankment, immediate decline, and consolidation on the embankment.

4. The time of consolidation on embankments is much shorter than the time of consolidation of soils under embankments. The relationship between the percentage of embankment decreases with time is stated by the regression equation as follows:

$Y1 = 0.0163 . \ln (x) + 0.2703$ for the sample location in the upper river area.

$Y2 = 0.0512 . \ln (x) + 0.2987$ for the sample location downstream of the river.

dengan:

Y is the ratio between the percentage of embankment reduction to the height of the initial embankment and x is the time of decline (month).

Acknowledgements

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