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Settlement Monitoring of Embankment Dams: Case Study of Gurara Dam, North Central Nigeria

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Abstract- Embankment Settlement in earth dam is common at post construction. Settlement also occurs during construction where compaction of fill materials is below optimum level specified in the design. This study analysed post Settlement of Gurara Multipurpose Dam built on the Gurara River near Abuja, the capital of Nigeria. Seven monitoring devices such as Electrical Vibrating Wire Piezometers (EVW), Standpipe Piezometers, Relief Wells, Finger Drains, Differential Settlement Monitoring (DSM), V-notch and Concrete Block Tape Extensometer were used in Gurara Multipurpose dam. Data obtained from DSM devices was used in the settlement analysis. Ten year (2004-2014) data were obtained at seven control stations of the crest settlement data of the embankment. There are seven sections and each section comprises of three DSM devices, except section 22 which has only two. The dimensionless parameter known as settlement index (S_i) and the percentage of the dam elevation P (%) that settled at each section were calculated for each of the seven sections. The measured difference in relative height $P(_{field})$ and the calculated percentage of the dam elevation P(%) that settled at each section were plotted to ascertain the deviation limit of the dam crest. The study showed that the maximum value of the settlement index (S_i) for each set of measurements at all sections was significantly lower than the threshold value of 0.02. Also the P (%) was less than 1% in all the sections indicating absence of creep or secondary consolidation of the embankment material.

Keywords- *Dam, Gurara River, Embankment, Instrumentation, Settlement, Basin*

I. INTRODUCTION

Dams are barriers to flow which are either constructed or natural. Dams which serve specific objectives such as hydropower generation, water supply, irrigation and flood control and recreation activities are man-made and are therefore, subjects of many scientific researches. The water impounded upstream of a dam is called a reservoir. The main purpose of a dam is to stabilize flow by storing water for use during low flow periods. Thus, water stored in a given reservoir during the rainy season can be used almost throughout the year (Ezugwu, 2013)[1]. A dam is a hydraulic structure of impervious material built across a flowing stream, river, or water channel to create a reservoir of impounded water for such purposes as water supply, irrigation, hydropower, flood and erosion control, navigation, fishing, recreation and other uses (Okoye 2014) [2].

The Gurara inter-basin water transfer scheme involves impounding water of River Gurara at Jere dam and from there water is transferred to Lower Usama Dam Abuja, the Federal Capital Territory, for municipal water supply and then to Shiroro reservoir to augment flow for the generation of electricity (FMAWRD, 1986) [3]

It is Nigeria's pioneer and largest water transfer scheme.

Gurara multipurpose Dam, a 3.2 Km long, 55m high composite rock fill with central clay core and crest width of 6m. It is constructed on a predominantly meridian trend of faulting significant irregularities of bedrock surface, which is weathered and had decomposed bedrock formed into layers of regional silty-clayed soil.

Monitoring is the collection, reduction, presentation and evaluation of the instrumentation data (Obamila and Oladele, 2012) [4]

The objective of the study was to evaluate the level of settlement of Gurara dam embankment, ascertain the level of deformation in the Gurara dam and predict the level of risks if any that could result from the settlement.

Settlement of Embankment Dams, if not effectively monitored, could be disastrous for the structural integrity of the dam. Settlement may lead to loss of free board and thus result in dam overtopping which could lead to dam failure and complete washing away of the dam and cause serious damage downstream of the dam.

The study reviewed the main features of the embankment and instrumentation devices incorporated into the embankment to accommodate the prediction and analysis of settlement of the fill material and the bedrock in the post construction era. The scope of this study was limited to the crest and downstream segments of the dam only as the upstream slope could not be accessed because the dam is fully impounded. The predicted settlement was compared with the actual readings obtained from the Dam Settlement Monitoring instruments to determine if the settlement was excessive.

II. STUDY AREA

The location of the study area is in the intermediate zone of Nigeria, between the semi-arid climate of the north and sub-humid climate of the south. The dam site is located on River Gurara in Kaduna State, at about 75 Km North -East of Abuja (Fig 1).

The Gurara and Kaduna River basins lie in the intermediate zone between semi-arid climate in the north and sub-humid climate in the south, and the (Repeated from last paragraph). The climate is influenced by the seasonal movement of the Intertropical Convergence Zone, which results in wet and dry seasons. Rain starts in May (or April) and lasts till October, with the peak rainfall occurring in September. The dry season lasts between November and March. The mean annual rainfalls of some locations in the scheme are as follows: 1300 mm at Minna, 1500 mm at Abuja, 1600 mm at Kafanchan, 1250 mm at Kaduna and 1400 mm at Jos. The mean monthly maximum and minimum temperatures in the basins are 37.3°C and 19.7°C, respectively, and the hottest months are February, March and April (Jimoh and Ayodeji, 2003) [5].

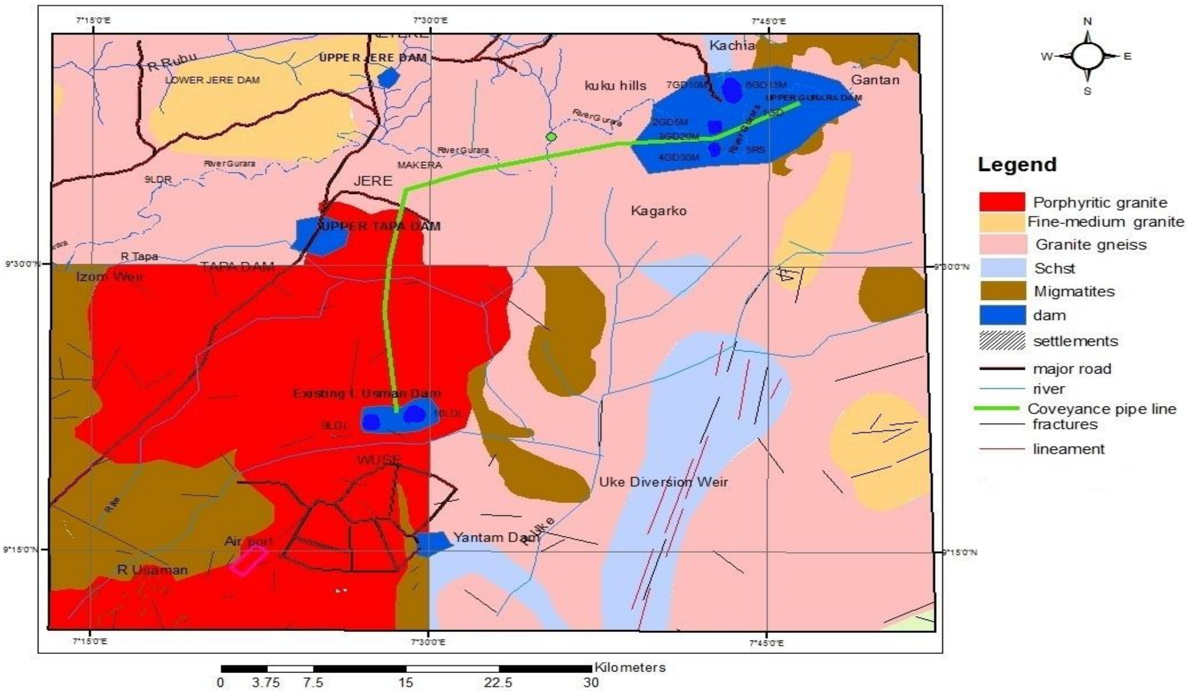

Figure 1. Map of the study area

III. METHODOLOGY

Instrumentation consists of the various electrical and mechanical instruments or systems used to measure pressure, flow, movement, stress, strain and temperature in a dam. For evaluation of safety of dams, instrumentation and monitoring must be continually carried out.

A. *Embankment Dams Instrumentation and Monitoring Devices*

The following devices are the instrumentation and monitoring devices installed at Gurara dam:

i. Electrical Vibrating Wire Piezometer (EVW)
ii. Stand Pipe Piezometers; A total of 32 piezometers were installed
iii. Relief Wells; A total number of 80 relief wells were installed along the length of the downstream dam toe excluding the rock fill section.
iv. Finger Drains; A total number of 49 finger drains were installed at the dam site.
v. *Differential Settlement Monitoring (DSM)* -There are 7 sections, and each section has 3 DSM including one reference except section 22 which has 2 DSM. Thus, the total number of DSMs is 20.

vi. *V-notch Weir* -Five temporary V-notch weirs have been installed, 3 along the left bank, 1 along the right bank and 1 along the rock fill zone where the coffer dam is located.

vii. *Concrete Block Tape Extensometer* - The tape extensometer is used to detect and monitor displacement or changes in distance between two reference points. A total of 21 extensometers are installed at the Dam.

The readings taken from the Dam Settlement Monitoring devices from 2008 to 2014 were used.

Figure 1 shows a typical DSM system setup at a section of the dam; this system consists of three gauging points and one reference point. Similar systems are setup at other sections of the dam to record the embankment settlement using a device which measures and monitors vertical displacement of the dam. The system is based on the principle of communicating vessels where each level gauge represents measuring point. Any vertical movement of the measurement point causes fluid redistribution in the circuit and thus level variation inside each gauge. The change in fluid level in each gauge corresponds to change in displacement. The signals are processed to obtain the differential displacement between the settlement gauge and the reference gauge. This is measured electrically by the sensor using a readout device.

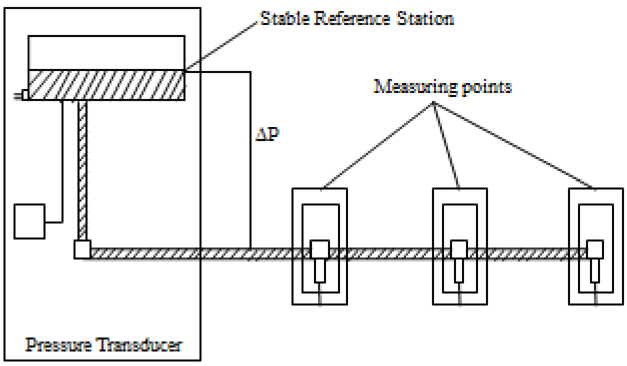

Figure 2. DSM system

There are 7 sections and each section comprises 3 DSM with one reference except section 22 which has 2 DSM. The total DSMs installed at the dam site excluding the reference gauges are 20. The seven sections are as follows: 11, 21, 22, 31, 32, 42 and 52. The section name is incorporated in the device name; for example, L11.1 is the first DSM device at section 11, L21.2 is the second DSM device at section 21 and so on. While L11.R is the reference gauge at section 11, L21.R is the reference gauge at section 21 and so on.

The crest settlement for the 20 gauge points was plotted against the time period to show the trend in the settlement data. The average percentage of the total elevation of the dam that has settled at each of the seven sections over the years was computed and plotted against the time period. These average percentages were checked against the industry standard which stipulates that the post-construction settlement of an earth embankment dam should not exceed 1% of the total height of the dam as a general rule of the thumb.

To calculate the percentage of the total elevation of the dam that settled at a section of the dam, the following equation is used:

$$P(\%) = \frac{s}{H_{total}}\% \quad (1)$$

Where, $P(\%)$ is the percentage of the dam elevation that settled at a section, s is the actual settlement at the section and H_{total} is the total dam elevation.

A dimensionless parameter known as settlement index was calculated for each of the seven sections. Equation 2 is the equation of the settlement index as reported by Pytharouli (2008) [6]

$$S_i = \frac{s}{1000 \,.\, H \,.\, log(\frac{t_2}{t_1})} \quad (3)$$

Where S_i is settlement index, s is the crest settlement measured in mm between time period t_1 and t_2 since the completion of the embankment at a section of the dam H meters high (Charles, 1986). [7] Values of $S_i > 0.02$ indicate that mechanisms other than creep or secondary consolidation of the embankment dam material contribute to dam settlements (Tedd et al., 1997) [8]. Settlement index is analogous to the coefficient of secondary consolidation for a clay soil.

Pytharouli (2008) [9] identified the other mechanisms other than the creep or secondary consolidation affecting crest settlement of the Kremasta dam in Greece as:

1) Reservoir level fluctuation and
2) Rainfall

So, if the value of $S_i > 0.02$, this means that other than creep or secondary consolidation, the other mechanisms mentioned above are responsible.

The average settlement index at each section can be plotted against the time period to obtain seven time series consisting of the values of the average settlement index for each of the sections. However, in order to simplify the procedure, a single time series consisting of the maximum value of all seven time series for each sampling interval, that is, a time series representing the envelope of the time series describing the settlement index for all seven survey points was considered in this work.

IV. RESULTS PRESENTATION AND ANALYSIS

A. *Dam layout*

The dam presents three different profiles as follows:

- A rockfill dam with central clay-core profile (this is called “rockfill dam”) it is about 500m long in the central part of the valley.

- A random fill dam profile (this is called “random fill”) it is about 1320m long in the right bank and 1230m long in the left bank.
- Two transition parts between the random fill wings and the rockfill wing (these are called “transition dams”) and both are 100m long.

The total length of the Gurara dam can be derived from the given information above. That is, $(500m + 1320m + 1230m + 2(100m)) = 3250m\ (3.25km)$ thus the total length of Gurara dam is $3.25km$. This is shown in the cross-section of the Gurara dam embankment below:

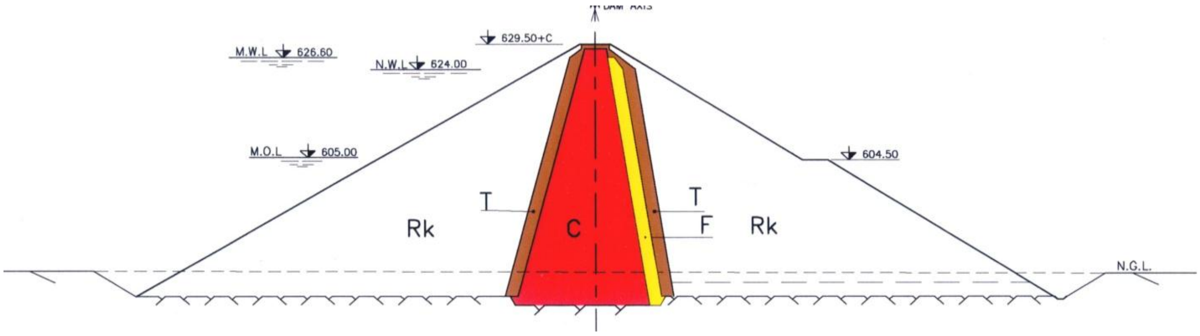

Figure 3. A Cross-Section of the Rockfill Section of Gurara Multipurpose Dam Embankment. Source: Final Design Technical Report, Gurara Dam, 2002 [10]

TABLE I. DAM CHARACTERISTICS

· Reservoir		
Normal Water Level (NWL)	masl	624
Maximum Water Level (MWL)	masl	626.6
Minimum Operating Level (MOL)	masl	605
Reservoir area at NWL	Km^2	55.4
Total reservoir capacity at NWL	Mm^3	882
Dead storage at MOL	Mm^3	175
Active storage	Mm^3	707
Dam		
Type		Embankment dam with 3 different sections
		Rockfill, random fill and transition dam
Elevation of top of dam	masl	629.5
Total length of top of dam	m	500m (rockfill dam) +2550m (random fill dam) +200m (transition) =3250m (total)
Maximum height above foundation	m	55
Total volume	m^3	7880000
Upstream face slopes	H/1V	1.6 (rockfill)
		3.2 (3.5 under berm EL.604.5) (random fill)
Downstream face slopes	H/1V	1.5 (rockfill) berm at EL.604.5 masl

B. Data from Differential Settlement Monitoring (DSM) devices

Apart from dam characteristics table as shown above, data were collected from Differential Settlement Monitoring devices which were installed along the dam crest to monitor the vertical displacement or settlement of the dam.

TABLE II. EMBANKMENT SETTLEMENT RECORDS

Device name	Installation/Reading date	Chainage	Offset (m)	Installation level (m)	Reading (mA)	Relative Height (m)	Relative Movement (mm) ΔH
L11.1	2/11/2007	1 + 820	-11.84	605	5.84	0.994	-233.95
	22/11/2010	1 + 820	-11.84	605	6.36	1.274	-612.97
L11.2	2/11/2007	1 + 820	-32.84	605	5.78	0.944	-180.89
	22/11/2010	1 + 820	-32.84	605	6.08	1.106	-442.29
L11.3	2/11/2007	1 + 820	-53.84	605	5.66	0.846	-78.37
	22/11.2010	1 + 820	-53.84	605	5.8	0.922	-253.43
L11.R	2/22/2007	1 + 820	-74.85	606	14.75	0.037	-564.25
L21.1	5/8/2004	1 + 191	-16.56	587	6.1	1.135	-10.56
	6/8/2007	1 + 191	-16.56	587	6.23	1.205	-63.62
L21.2	5/8/2004	1 + 191	-34.56	587	6.02	1.081	-15.93
	5/8/2007	1 + 191	-34.56	587	6.21	1.183	-101.22
L21.3	5/8/2004	1 + 191	-52.56	587	6.07	1.087	-10.56
	6/8/2007	1 + 191	-52.56	587	5.95	1.022	-70.89
L21.R	5/8/2004	1 + 191	-70	588.13	11.3	0.0279	
	6/8/2007	1 + 191	-70	588.13	13.81	0.0448	
L22.1	27/5/2007	1 + 191.26	-13.75	605	5.02	0.613	-5.1
	24/5/2010	1 + 191.26	-13.75	605	5.18	0.699	-106.24
L22.2	27/5/2007	1 + 071	-26.75	605	5.03	0.596	-10.27
	24/5/2010	1 + 071	-26.75	605	5.14	0.655	-73.98
L22.R	27/5/2007	1 + 071	-61.53	605.7	13.65	0.0456	
	27/5/2010	1 + 071	-61.53	605.7	11.45	0.037	
L31.1	1/3/2005	1 + 065	-15.9	587	6.21	1.131	-10.23
	5/3/2007	1 + 065	-15.9	587	6.26	1.158	-32.53
L31.2	1/3/2005	1 + 065	-48.9	587	6.12	1.109	-15.61
	5/3/2007	1 + 065	-48.9	587	6.35	1.233	-134.85
L31.3	1/3/2005	1 + 065	-81.9	587	6.17	1.123	-4.85
	5/3/2007	1 + 065	-81.9	587	6.33	1.209	-86.59
L31.R	1/3/2005	1 + 065	-107	588.14	13.6	0.0457	
	5/3/2007	1 + 065	-107	588.14	14.28	0.0504	
L32.1	7/3/2007	0 + 071	-12.69	605	4.61	0.338	0.94
	22/03/2010	0 + 071	-12.69	605	5.2	0.655	-313.34
L32.2	7/3/2007	0 + 071	-30.69	605	4.95	0.344	6.37
	22/03/2010	0 + 071	-30.69	605	5.59	0.688	-337.71
	22/03/2010	0 + 071	-50.69	605	4.78	0.35	-47.42
L32.R	3/6/2007	0 + 071	-61.53	605.42	14.46	0.0508	
	22/03/2010	0 + 071	-61.53	605.42	14.48	0.0509	
L32.2	7/3/2007	0 + 071	-50.69	605	4.72	0.318	-15.22
L42.1	22/5/2006	0 + 940	-11.74	605	6.04	0.664	-9.64
	22/4/2009	0 + 940	-11.74	605	8.59	2.039	-1382.22
L42.2	22/5/2006	0 + 940	-32.74	605	5.32	0.675	-5.33
	22/4/2009	0 + 940	-32.74	605	5.88	0.978	-306.5
L42.3	22/5/2006	0 + 940	-53.74	605	5.38	0.659	-5.34
	22/4/2009	0 + 940	-53.75	605	5.7	0.829	-173.55
L42.R	22/5/2006	0 + 940	-77.83	605.67	13.14	0.0453	
	22/5/2009	0 + 940	-77.83	605.67	13.77	0.0473	
L52.1	25/5/2006	0 + 831	-11.8	605	5.37	0.597	-4.88
	25/2/2009	0 + 831	-11.8	605	6.65	1.285	-691.62
L52.2	25/5/2006	0 + 831	-32.8	605	5.67	0.668	0.5
	25/5/2009	0 + 831	-32.8	605	8.2	2.03	-1360.63
L52.3	25/5/2006	0 + 831	-53.8	605	5.21	0.651	-4.89
	25/2/2009	0 + 831	-53.8	605	5.42	0.764	-116.65
L52.R	25/5/2006	0 + 831	-77.5	605.68	17.71	0.0484	
	25/5/2009	0 + 831	-77.5	605.68	13.9	0.0497	

The following convention was adopted in naming any DSM device installed at the dam site:

L11.1 (605/-11.84/1+820)

Where,

L11.1 is the name of the device, 605 represents the installation level, -11.84 represents the device offset and 1+820 is the chainage at which the device is located. The data sheet, showing the various settlements recorded for all the devices over the years, can be found in the appendix of this work.

The data used for the analysis were randomly collected from data recorded from 2004 to 2014 at the twenty seven control points which were named as indicated above

C. Calculations of P(%) and S_i for the 7 Sections of DSM

Initial data of 2004, 2005, 2006, 2007 and corresponding three years data (2007, 2009, 2010) was used as the final data in the calculation for the computations of P (%) and S_i.

For L11

L11.1 after 3yrs.:-

$s = \Delta H_{2010} - \Delta H_{2007} = -612.97 - (-233.95) = -379.02mm$

$= -0.379m$

$H = H_{2010} - H_{2007} = 1.274 - 0.994 = 0.28m$

$$P\ (\%) = \frac{-0.379}{1.274} = -0.297\% < 1\%$$

$$S_i = \frac{-0.379}{1000\left(1.274\right) \text{Log}\left(3/1\right)} = -0.0006235 < 0.02$$

The computations were repeated for the other sections and the results are plotted in Figs 4 and 5. The results show that the value of P% (Percentage of total elevation that settled in all the sections of the embankment) is less than 1%. Also the value of S_I (Settlement index) in all the sections of the embankment is far less than 0.02.

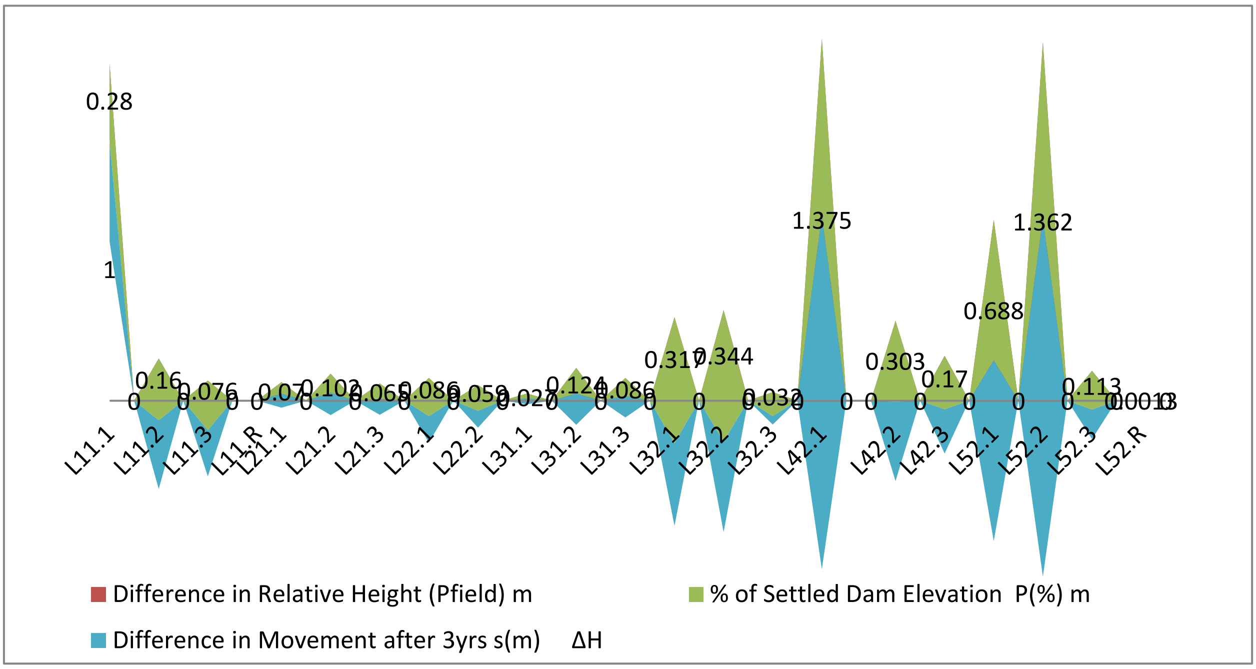

Figure 4. Percentage of Settled Levels

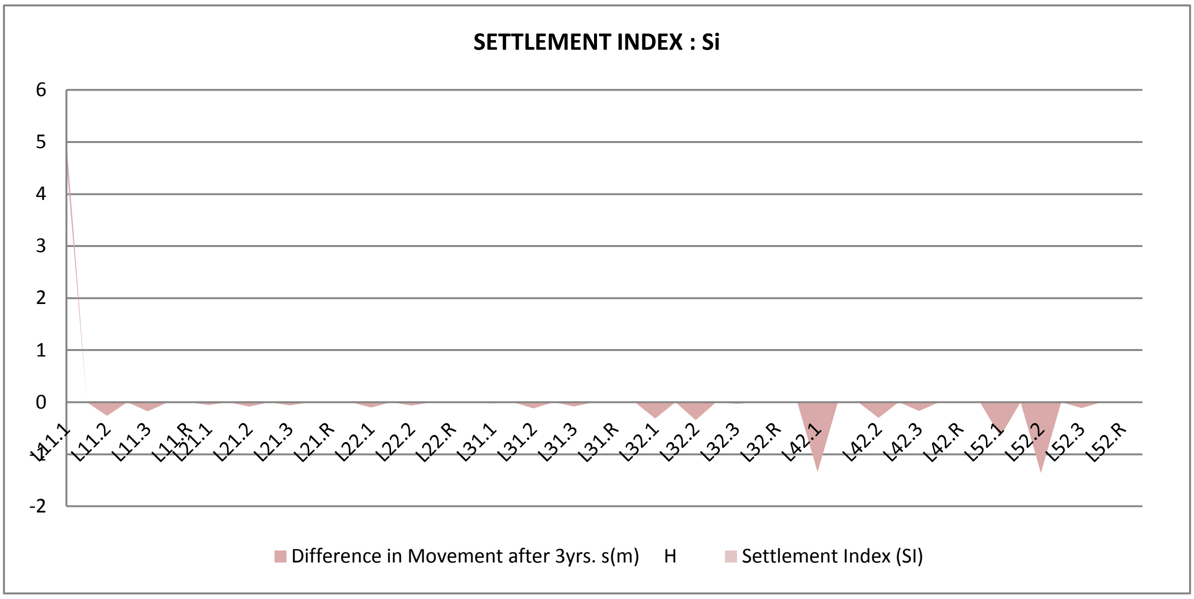

Figure 5. Settlement Index

V. CONCLUSION

From the outcome of this research, it is concluded that:

i. The value of P% (Percentage of total elevation that settled in all the sections of the embankment) is less than 1% meaning that the post construction settlement of the embankment is very much within the standard.

ii. The value of S_I (Settlement index) in all the sections of the embankment is far less than 0.02. This indicates absence of creep or secondary consolidation of the embankment material.

iii. Values obtained from settlement calculations at all sections of the dam embankment are very negligible indicating that there have been no unsafe developments on the embankment.

iv. It is also evident based on the various graphs plotted that the Gurara dam embankment is performing as expected according to the design and construction.

Finally, we recommend that;

i. There should be timely and adequate maintenance of the dam embankment instrumentations particularly DSM instrumentations at the dam site.

ii. Periodic settlement studies should be carried out to ascertain the condition and level of safety of the dam. The studies should be extended to foundation settlements.

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