Practical Method of Predicting Slope Failure Based on Velocity Value (SLO Method) From Slope Stability Radar

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Predicting slope failure is one of the most sought after feature from Slope Stability Radar (SSR). An accurate slope failure prediction will potentially give an ample time to manage risk related with slope stability, wherein the evacuation of equipment or personal would be executed on a timely manner. The renowned method to predict failure among geo-mechanical practitioner is utilizing inverse velocity method, in which collapse will be predicted to happen when the extension of inverse velocity line is intercepted at predefined value that is usually only fractal above zero. The tenet of this method is, if one has acquired the knowledge of inverse velocity value from previous collapses, the next collapse could be predicted based on it with the pretext that both share the same nature and geological feature. The same can be said for predicting collapse based on velocity value. Set of maximum velocity value from several previous collapses will be averaged to determine predefined assumption to predict the next collapse. This paper will demonstrate an alternative method to predict collapse that will use velocity value instead of inverse velocity. This method is called SLO method as proposed by Azania Mufundirwa. This paper will specifically exemplify the practical steps to produce the failure prediction from slope stability radar data, and discuss the characteristic of the prediction yield by this method. Velocity chart with velocity calculation period of 60 minutes is first established from particular pixel deemed as the one that showing the most distinguished progressive deformation trend. The velocity data will then be an exported and reprocess as such that the time data will be converted into unit time stamp number. The designated time stamp will then be accumulated, in which the onset of failure, will be regarded as time 0 reference. Log linear chart will be generated in which X-axis will be occupied by velocity value, while Y-axis will depict Velocity x Accumulated time (SLO chart). Collapse can subsequently be predicted by intercepting the predefined assumption of velocity during collapse with the log linear curve from the SLO chart. Two methods, mathematical & graphical, will be presented in this paper in order to give in depth understanding as to how one can predict collapse event with velocity value. Taking account on the study case from iron ore mining, SLO method yielded prediction of failure time on 10:58 PM 31st January 2016, meanwhile the real failure occur on 11:32 PM 31st January 2016.

Key words: Slope Stability Radar, Slope Failure, Velocity, SLO Method

Introduction

Indonesia, an archipelagic nation at the heart of South East Asia region, is bestowed with set of features such as topography steepness, geological condition, soil moisture condition (inherent with the characteristic of the climate), rate of precipitation, and earthquake likelihood in an unique mixture that render the nation to be fairly susceptible to landslide or failure. Previous studies by different researcher have revealed an approximation of conclusion and number. Geological Agency of Indonesia relays, within the period of 2003-2007, rapid landslides have caused an average of 32 casualties per event (Cepeda J, et al 2010). The global catalogue authored by Krischbaum et al. which stretch the year of 2003, and from 2007 to 2009, reveals 97 landslides in Indonesia, which yielded 872 casualties. All the fact & figures inevitably urges every agency and authority involved to address this landslides and its consequence issue. The interference from human activity, taking its baldest shape in the form of mining activity, needless to say only augmented the probability of the risk. A study being conducted by Indonesia Rock Mechanic Society revealed a quite staggering number. Across the period of time from 2012 to 2016, failure related accidents in mining industry are taking account of 43%, 16%, 36%, 30%, and 17% respectively from total of mining accidents in Indonesia (Gunarto, 2017). To date, either rapid failure or slow moving landslides still couldn't be eradicated completely by any means or form of technology. The best option that could be relied upon is to detect the potential of slope instability that could develop into a landslide or failure. Thereafter, a systematic failure prediction shall be generated to give a sufficient warning and timing of evacuation for all the infrastructure and people influenced by the impact of the failure.

Slope stability radar, which depends on the interferometry method to measure miniscule deformation, is arguably the most accurate monitoring tools that could provide both risk related with slope instability detection and further failure prediction (Noon, et al, 2001). For the latter, it was the obviously the most sought after feature for agency or division that involved in any effort to manage slope stability risk in open pit mine. Notwithstanding the rapid development of technology, failure prediction is still pretty much depended on the capability of the slope stability radar operator to utilize the right concept or method to predict the penultimate failure. Slope stability radar is a mere tool, while any value that could be extracted from it, is relied upon the people who analyze the data. For some particular reasons, mankind is still a far cry from fully automated radar for slope stability monitoring. Therefore this paper will emphasize on how rock mechanic practitioner could utilize particular method to predict failure within the framework of slope stability radar data, especially in the field of open pit mining.

This paper will explore the concept of failure prediction based on velocity value, the so called SLO method, introduced by Azania Mufundirwa in his paper titled "Practical Method for Prediction of Geo-mechanical Failure-time" (Mufundirwa, 2008). While the aforementioned paper put more emphasize on theoretical and laboratory work as the underlying foundation for the postulation of SLO method to predict failure, this paper will elaborate on how this SLO method could be put into practice within the platform of slope stability radar data. This method will be of fair interest, because among the geo-mechanic practitioner well exposed to the utilization of slope stability radar, it is inverse velocity instead of velocity which universally being used to predict landslide. This renowned method to predict failure among geo-mechanical practitioner is utilizing inverse velocity value, in which collapse will be predicted to happen when the extension of inverse velocity line is intercepted at predefined value that is usually only fractal above zero (Rose, et al 2007). The following discussion will convey the concept of SLO and the practical step to apply the method on slope stability radar data.

SLO Method to Predict Slope Failure

Azania Mufundirwa in his paper titled "A Study on Prediction of Geomechanical Failure-time & Rock Deformation" proposed the usage of velocity value to predict failure. He composed the theory of this method from the precedent analytical model for tertiary creep rock by Okubo and Fukui. The original equation is as below:

$$\varepsilon\varepsilon = -BB\log(TT_{ff} - tt) + CC \quad (1)$$

In which $\varepsilon\varepsilon$: strain, tt: time, TT_{ff}: failure time, $TT_{ff} - tt$: life expectancy, while BB & CC are constants. Mufundirwa thereafter substitute strain with displacement, and differentiate both side into the equation below:

$$\frac{dddd}{dddd} = \frac{BB}{TTff - dd} \quad (2)$$

$\frac{dddd}{dddd}$ is the displacement rate or velocity. Rearrangement of equation (2) will yield equation that will be utilized in this paper to predict the failure.

$$tt\frac{dddd}{dddd} = TTTT\frac{dddd}{dddd} - BB \quad (3)$$

Equation (3) could be further crafted into the creation of SLO chart, that will depict $\frac{dddd}{dddd}$ or velocity as the xx-axis, and $tt\frac{dddd}{dddd}$ or time multiply by velocity as the yy-axis. Below was the example of SLO chart taken from the aforementioned paper authored by Mufundirwa.

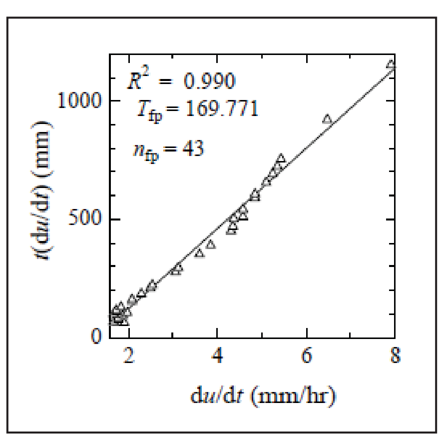

Figure 1. Theoretical SLO chart inferred from velocity and time data.

Prediction for failure based on velocity value in this paper will be augmented by at least 2 factors. First is the computed deformation and time data as it were generated on quasi-real time fashion by the slope stability radar. This will allowed well spacing and good distribution of data for the calculation process to yield the failure prediction. Last but not least, the thing that wasn't explicitly mentioned on

Mufundirwa's paper is the collaboration of empirical study to enhance the accuracy of failure prediction. Rather than predicting the life expectancy of the slope, previous empirical study that involve the registration and simple statistical calculation of maximum velocity of slope failures will be used to predict the failure by intercepting the trend lines of SLO chart with $\frac{dddd}{dddd}$ or velocity value.

Study Case for the Application of SLO Method

In this paper, a study case derived from iron ore mining will be selected as an example as to how SLO method could be utilized to predict slope failure. Both the geological condition from the mine-site and the empirical observation of previous failures cases will be scrutinized in order to construct an in depth understanding of the next failure that might happen. The mine-site coded as SCM area is located on Middle Miocene Formation intersected by some magmatic intrusion. Sedimentology rock layering was an obvious feature that could be observed on the slope. On top of that there is 1 additional geological feature which seemingly played a major role in affecting the slope instability of the mine site that is the occurrence of geological structure such as fault and joints which dissected the slope of the mine site. These factor in an interplay with the artificial nature of slope on the mine site, which yielded by the engineering work on course to extract the commodity, have resulted several cases of failures with particular characteristics shown as below.

Table 1. Tabulation of data from previous 5 failures on study case area.

No	Time of failure occurrence	Maximum velocity (mm/hr)	Failure mechanism
1	May 15th 2015 10:05 AM	29.34	Wedge failure
2	June 10th 2015 03:23 PM	27.50	Wedge failure preceded by rain
3	June 15th 2015 08:05 PM	31.43	Wedge failure
4	November 20th 2015 10:09 PM	30.44	Wedge failure
5	December 2nd 2015 12:22 AM	28.56	Wedge failure

Two points could be emphasized from above data that in turn will provide important cue to predict the next failure on the mine-site. First and foremost is the similarity of the failure mechanism taking place on the mine-site. Wedge failure is the modus operandi of all the previous failure that has happened on SCM area. Provided with this fact, if based on field observation geotechnical engineer has observed the telltale sign of slope instability due to the occurrence of two or more sets of joints crisscrossed each other, a considerable amount of confidence could be attained to predict the impending failure by SSR. Moreover the registered set of maximum velocity value could be statistically processed in order to predefine the value that will act as a projection for the SLO method. In this paper, the average value of 5 previous failure cases will be used as the projection value, which is 29.45 mm/hr. For the sake of simplicity and to incorporate some measure of safety conservatism the value that will be used is precisely 29 mm/hr.

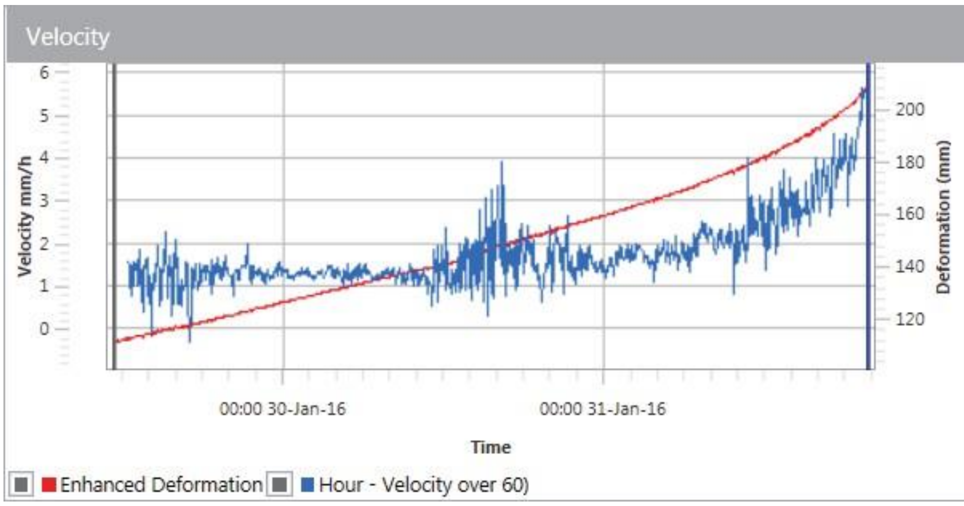

Figure 2. An overlay of deformation and velocity charts, using a 60 minutes of velocity calculation period.

The next step to predict failure, after the determination of velocity value as a projection value, is generating the SLO chart. Taking account the study case of SCM area, a progressive deformation trends have been observed on a discrete area. Velocity chart with velocity calculation period of 60 minutes, as shown in **Figure 2,** is first established from particular pixel deemed as the one that showing the most distinguished progressive deformation trend. The velocity data will then be exported and reprocessed as such that the time data will be converted into unix time stamp number. The designated time stamp will then be accumulated, in which the onset of failure, will be regarded as time 0 reference. Log linear chart will be generated in which xx-axis will be occupied by velocity value, while yy-axis will depict Velocity × Accumulated time (SLO chart). Collapse can subsequently be predicted by intercepting the predefined assumption of velocity during collapse with the log linear curve from the SLO chart. Two methods, mathematical & graphical, will be presented on ward to give an explicit illustration of the SLO method.

Mathematical Method of SLO

After exporting the deformation and velocity graph from SSRViewer into a spreadsheet, a column of nn_{ffff} should be added listing from 1 to the end of the table. But first, make sure to cut the table just after the on-set failure occurred. Time should be shown as timestamp when exporting the data, therefore it will be shown in seconds rather than in date and time format. Scan time can be acquired by subtracting time with the one before, and are shown also in seconds, to be added in another column. The accumulated time (tt) after each scan can be acquired by multiplying each nn_{ffff} number with each of the time per scan. Thus, the tt^{dddd}_{dddd} is obtained by multiplying tt with velocity. The graph can now be made by using the $tt\frac{dddd}{dddd}$ as yy-axis and the velocity as xx-axis.

Table 2. Spread sheet exported from SSR which has been processed in order to establish the SLO chart.

Time	Time Stamp (s)	Enhanced Deformation (mm)	Velocity (VCP 60) (mm/h)	nfp	Scan Time (s)	t (Accumulated Time) (s)	V x t (mm.s/h)
31/01/2016 10:02	1454227320	176.5284	1.575958	1	0	0	0
31/01/2016 10:06	1454227560	177.1896	2.05011	2	240	240	492.0264
31/01/2016 10:10	1454227800	177.3551	1.96402	3	240	480	942.7296
31/01/2016 10:15	1454228100	177.1528	1.693802	4	300	780	1321.16556
31/01/2016 10:19	1454228340	177.8325	2.299454	5	240	1020	2345.44308
31/01/2016 10:23	1454228580	177.9751	2.189575	6	240	1260	2758.8645
31/01/2016 10:27	1454228820	177.9203	1.858536	7	240	1500	2787.804
31/01/2016 10:31	1454229060	178.2009	2.407242	8	240	1740	4188.60108
31/01/2016 10:35	1454229300	178.0344	1.640686	9	240	1980	3248.55828
31/01/2016 10:40	1454229600	177.99	1.551819	10	300	2280	3538.14732
31/01/2016 10:44	1454229840	178.4068	2.067413	11	240	2520	5209.88076
31/01/2016 10:48	1454230080	179.3578	4.021988	12	240	2760	11100.68688
31/01/2016 10:52	1454230320	178.893	2.178635	13	240	3000	6535.905
31/01/2016 10:56	1454230560	179.4197	2.35643	14	240	3240	7634.8332
31/01/2016 11:01	1454230860	179.4111	2.232178	15	300	3540	7901.91012
31/01/2016 11:05	1454231100	179.6392	3.110886	16	240	3780	11759.14908
31/01/2016 11:09	1454231340	179.6693	2.479675	17	240	4020	9968.2935
31/01/2016 11:13	1454231580	179.5867	2.231598	18	240	4260	9506.60748
31/01/2016 11:17	1454231820	179.9688	2.815933	19	240	4500	12671.6985
31/01/2016 11:21	1454232060	180.1467	2.314224	20	240	4740	10969.42176
31/01/2016 11:26	1454232360	180.3755	2.400467	21	300	5040	12098.35368
31/01/2016 11:30	1454232600	180.0797	2.159363	22	240	5280	11401.43664
31/01/2016 11:34	1454232840	180.3575	2.156601	23	240	5520	11904.43752
31/01/2016 11:38	1454233080	180.8974	2.862961	24	240	5760	16490.65536
31/01/2016 11:42	1454233320	181.1235	3.133484	25	240	6000	18800.904
31/01/2016 11:47	1454233620	181.2144	2.807632	26	300	6300	17688.0816
31/01/2016 11:51	1454233860	181.5426	2.184769	27	240	6540	14288.38926
31/01/2016 11:55	1454234100	181.8586	2.96553	28	240	6780	20106.2934
31/01/2016 11:59	1454234340	181.3607	1.940994	29	240	7020	13625.77788
31/01/2016 12:03	1454234580	181.8465	2.43544	30	240	7260	17681.2944

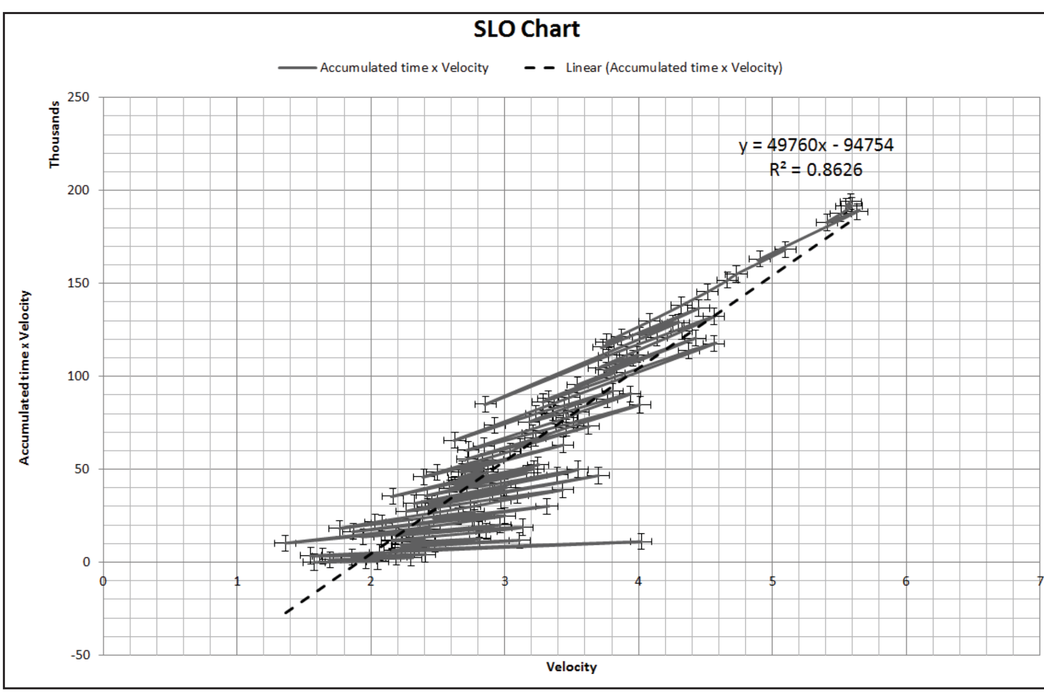

Figure 3. SLO chart generated from study for the mathematical method.

Get the linear equation from the graph. The value of xx which is the velocity will be 29 mm/hr, and is acquired from the previous statistical calculation of 5 previous failure cases on the mine site. From that, one will get:

Table 3. The result of SLO mathematical method.

xx	$29\ mmmm/h$
yy	$1348286\ mmmm\ ss/h$
tt	$46492.62069\ ss$
$tt\ (iiii\ ttiimmtt)$	$12: 54: 53$

The value of tt that was acquired from the linear equation above is the amount of predicted time passed since the time of $ii_{ffff} = 1$, which is January 31, 2016 at 10:02 AM. This would make the predicted time of failure to be January 31st , 2016 at around 10:56 PM.

Graphical Method of SLO

SLO chart for the graphical method will be produced with the same manner as the one for mathematical method, with some particular adjustment. One needs to extend the xx-axis of the chart, that is the velocity value axis, as such that the value will be up to slight above 29 mm/hr. This is intended to allow the interception of the SLO trend line with xx-axis and yy-axis. First value of 29 mm/hr at the xx-axis will be marked and vertical line will be projected until it intercepts the SLO trend line. The point of interception will then be marked and horizontal line to the left will be extended until it reached the yy-axis. The value at the yy-axis, accumulation of time multiply with velocity, will then be estimated. In this case, the obtained value was 135,000 mm s/hr. The obtained value step is then divided by 29 mm/hour resulting the estimated duration time from ii_{ffff} 1 to time of failure (1350000/29 = 46551.73 second = 12.93 hours). The prediction time of failure is obtained by addition of ii_{ffff} 1 and duration time (ii_{ffff} 1 occurred on 31/01/2016 10:02 and estimated duration time is 12.93 hours or 12 hours 56 minutes, thus the failure is predicted to be occurred on 31/01/2016 10:58 PM.

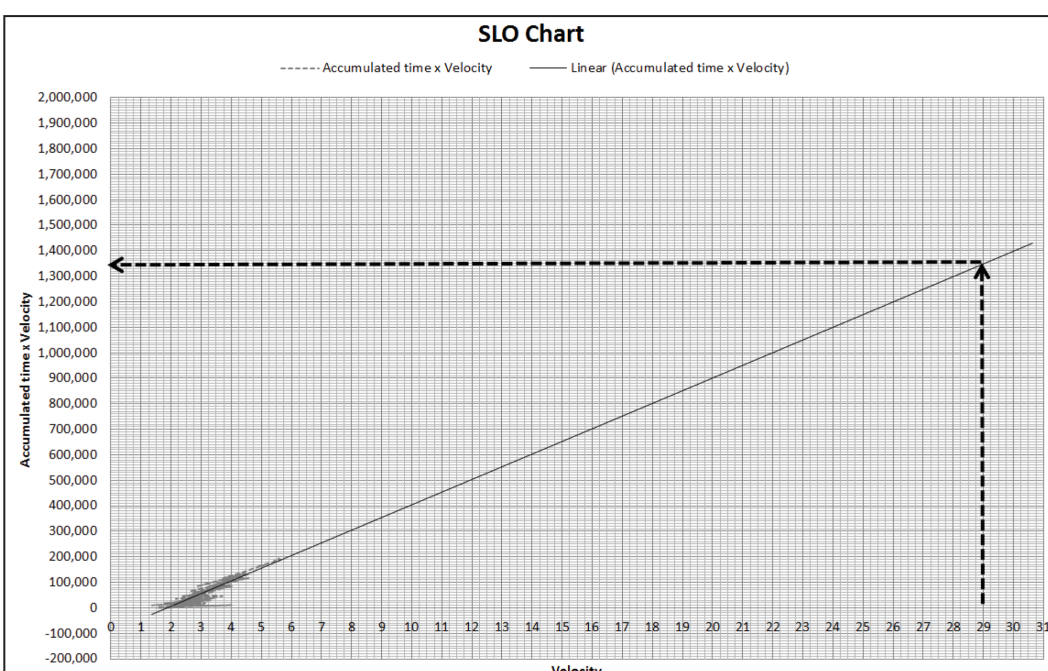

Figure 4. SLO chart generated from study case for graphical method.

Discussion

A time of failure prediction can be deemed as beneficial to all parties related with the effort to manage slope instability risk only if it provides result which preceded the real failure with only considerable discrepancy. The progressive deformation trend from SCM area on which first detected on 31st January 2016 10:00 AM transpired as such that it eventually underwent failure at January 31st 2016 11:32 PM. Comparing this with the time of failure prediction revealed that SLO method able to provide a sound prediction that is around 30 minutes before the real failure happen. The set of data that being use as the backbone of the SLO chart was up to January 31st 2016 07:41 PM, which means with the prediction that has been attained there are time window of 3 hours and 15 minutes between the latest data being used and the resulted prediction. Provided the SLO method takes around 15 minutes to be put into practice, then it can be well said that there are 3 hours of time window to address the impending failure that about to happen. It is arguably an ample time window that will give flexibility for geotechnical engineer to plan for the evacuation, access closure, or other measure that need to be undertook to address the hazard. One note that needs to be highlighted is since this SLO method is much depended on trend line of the SLO chart, the method needs to be retaken as the slope stability radar revealed new data or trend. The nn_{ffff} 1 can be modified as such so the distribution of data is less erratic, hence will automatically produce trend line with higher value of regression coefficient.

Conclusion

Taking account on the study case from iron ore mining, SLO method yielded prediction of failure time on 10:58 PM 31st January 2016, meanwhile the real failure occur on 11:32 PM 31st January 2016. The failure prediction proved to be of a good quality and accuracy, thus provide sufficient time window to manage the severity of the hazard.

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