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Statistically Defined Slope Deformation Behaviour Model Case Study: Upright-Dipping Highwall in A Coal Mining Area

[1] Lintang Putra Sadewa, [2] Ilham Prasetya Budhi

[1][2] Geotechnical Support Services, GroundProbe

Email: [1] lintang.sadewa@groundprobe.com, [2] ilham.prasetya@groundprobe.com

***Abstract*— The slope monitoring program has now become a mandatory campaign for open pit mines around the world to operate safely. Utilizing various slope monitoring instruments and strategies, miners are now able to deliver precise decisions in mitigating the risk of slope failures which can be catastrophic. Currently, the most sophisticated slope monitoring technology available is the Slope Stability Radar (SSR) which can measure wall deformation with submillimeter accuracy.**

The slope movement historical data that SSR collects can be analysed to better understand slope deformation behaviour which, due to the geological complexity that each site possesses, will vary distinctively. Experience shows that this information will be highly beneficial in determining site-specific variables such as setting up alarm thresholds.

In this paper, a total of 73 back analyses are carried out over the study period from which the slope-behaviour-defining parameters (e.g., deformation sequence, velocity, inverse velocity) are defined. The Anderson-Darling fitting test is then applied to each parameter and the sample mean values obtained are then used to illustrate an empirical model of slope deformation behaviour describing each of deformation sequence leading to slope failure.

The result shows that there are three consecutive slope movement sequences developed namely linear, progressive, and failure-to-post-failure. The fitting test reveals that each deformation sequence possesses variables with different distribution patterns and sample mean values. Additionally, a fitting test for coherence, a data attribute unique to SSR, is also given. Ultimately, comparison with actual data suggests that the sample mean of each parameter seems to represent very well.

***Index Terms*— Safety-Critical Monitoring, Fitting Test, Slope Deformation Behaviour Model, Coal Mining**

I. INTRODUCTION

This study attempts to determine an empirical model of slope deformation behaviour that is defined statistically from deformation data captured by the Slope Stability Radar (SSR) from January to October 2022. The study area comprises of upright-dipping highwall setting in a coal mining area with intense mining activities. The Anderson-Darling fitting method is used to obtain the sample mean of each parameter with three types of distribution (normal, log-normal, and gamma). The model intends to be site-specific in nature thus valuable information extracted (e.g., time-to-failure, onset-of-acceleration, and velocity) will give a clear understanding of how deformation trends evolve over the area.

II. METHODOLOGY

This study focused on rock slope failures that occurred in a coal mine with an upright-dipping highwall from January to October 2022. A total of 73 rock collapses were recorded by two ground-based radars over the same wall. Back analysis of the failures is performed one by one to characterise the deformation sequences. That sequence includes total linear deformation time, velocity on the linear stage, minimum and maximum velocity on the progressive stage, maximum and minimum inverse velocity, time-to-failure, and coherence. The data are then tabulated and tested using the Anderson-Darling Fitting and Probability Method via Minitab. The mean obtained after the test will be used to determine the empirical model. The detailed geological background and the effect of vector loss are not discussed in this study.

Slope stability radar detects slope deformation using the interferometry concept [6]. It transmits an electromagnetic wave to the object (slope surface) and receives the reflected wave. The reflected wave will be red by the radar as one phase. This repeated process will produce one phase each, and phase change from the 2 consecutive scans will be processed to obtain a displacement (Fig. 1). Since the radar scanning continuously, the deformation data is processed into a deformation plot. This plot will be analysed to determine the deformation trend, velocity, inverse velocity, and velocity ratio [9]. The other parameter including on-set-of-failure and time-to-failure will be obtained from the deformation and velocity plots (Fig. 2).

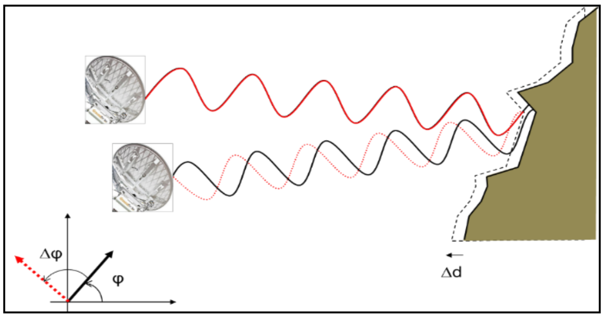

Fig. 1: Radar wall scanning process [4].

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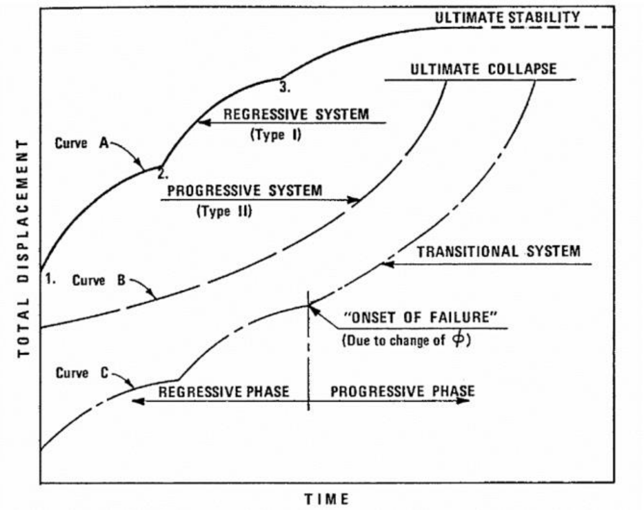

Fig. 2: Typical displacement time behaviour for pit slope failures [2].

Slope stability radar from GroundProbe also has a coherence attribute. Coherence is a consistency of the amplitude and range that has a range from 0 to 1. The coherence value is obtained from a normalized cross-correlation function of amplitude in relation to range measurement. No change in amplitude and range data reflected with 1. Otherwise, if there is any disturbance on the object/wall the amplitude and/or range changes, and the coherence value drops as well [3]. A slope failure will have a change in amplitude and range data. The drop in coherence value after a progressive deformation trend will be determined as a failure time.

The fitting test is conducted to a series of parameters derived from the back analysis to obtain the sample mean. This study uses the Anderson-Darling method, one of the most powerful tests even for a small sample size [7]. The power test performed by Stephens [8] also mentioned that the Anderson-Darling test is the most powerful EDF (Empirical Distribution Function) test in widely varying circumstances. There are many options of distribution types available such as normal, log-normal, gamma, Weibull, etc., and only the first three mentioned types are used in this study. AD and P-values will help to determine which one is the best distribution for each parameter. If the P-value is below the significance level (α=0.05), the hypothesis is rejected or the dataset does not fit any distribution. On the other hand, if we have P-values from several distributions that satisfy the hypothesis, look at the smallest AD value to determine the best fit [5]. Below is the general A-D test (1).

$$W_n{}^2 = -n - \frac{1}{n}\sum_{j=1}^{n}(2j-1)\left[\ln u_j + \ln(1-u_{n-j+1}\right] \quad (1)$$

Once the dataset fits the normal distribution, the mean will be obtained directly from the total value divided by the amount of data. However, if the data fit the other distribution type, the following equation will be used to determine the mean and standard deviation. Equation (2&3) is for lognormal distribution and (4&5) is for gamma distribution.

$$M = e^{\mu+\frac{1}{2}\sigma^2} \quad (2)$$

$$SD = \sqrt{e^{2\mu+\sigma^2}(e^{\sigma^2-1})} \quad (3)$$

$$M = \alpha\beta \quad (4)$$

$$S = \alpha\beta^2 \quad (5)$$

Mean (M) and standard deviation (SD) for the lognormal distribution involve location (μ) and scale (σ). Whereas gamma distribution use shape (α) and scale (β) as calculation parameters.

III. RESULT AND DISCUSSION

A. Statistical Analysis: Anderson-Darling Fitting and Probability Test

A total of 73 rock slope failures from January to October 2022 are back analysed. Table 1 summarizes the values of AD and P-Values at the significance level of 5% (α = 0.05) for each type of distribution. The critical values for the normal and lognormal distributions are 0.752 and the critical values for the gamma distribution range are between 0.759-0.786 depending on the k value. Each parameter has at least one condition that satisfies the hypothesis. The lowest AD values for each parameter (highlighted in red) are the best distribution fit and will be used to determine the mean and standard deviation. All the best distribution fits are statistically reliable since the P-values are above the significance level (α = 0.05).

The result shows that each state of the failure sequence fits into different distribution pattern. For the linear sequence, linear time (duration) and velocity linear fit with the lognormal distribution. In the progressive state, five velocity datasets have tendencies to follow the gamma distribution, and the other three suits the lognormal distribution. The inverse velocities data are best fitted with the lognormal distribution with only one dataset following the gamma distribution. Time-to-failure data also has the best fit with the gamma distribution and the coherence dataset is the only one that has a normal distribution.

Table 2 which reports the calculated means and standard deviation. For the parameter that fit the normal distribution, the mean and standard deviation are directly obtained by dividing the total value by the data amount. Otherwise, for the parameter that follows the lognormal and/or gamma distribution, Equation 2 and Equation 4 are used respectively. The relative minimum value is calculated by subtracting the mean and minimum value, while the relative maximum value is a subtraction from the maximum value and mean.

Parameter		Normal		Lognormal		Gamma	
		AD	P-Value	AD	P-Value	AD	P-Value
Linear Time (h)		0.67	0.07	0.63	0.09	0.67	0.08
Velocity Linear (mm/h)		7.92	<0.005	0.64	0.09	1.91	<0.005
Progressive Velocity (mm/h)	60min	2.70	<0.005	1.06	0.01	0.34	>0.25
	60max	1.72	<0.005	1.44	<0.005	0.60	0.13
	180min	3.50	<0.005	0.64	0.09	0.32	>0.25
	180max	3.45	<0.005	0.27	0.66	0.76	0.05
	360min	3.32	<0.005	0.53	0.17	0.27	>0.25
	360max	4.19	<0.005	0.36	0.43	1.06	0.01
	720min	3.38	<0.005	0.66	0.08	0.41	>0.25
	720max	3.89	<0.005	0.25	0.75	0.85	0.03
Inverse Velocity (h/mm)	60max	1.87	<0.005	0.46	0.25	0.34	>0.25
	60min	2.86	<0.005	0.27	0.68	0.56	0.17
	180max	5.08	<0.005	0.25	0.75	0.84	0.04
	180min	2.65	<0.005	0.26	0.70	0.45	>0.25
	360max	4.85	<0.005	0.30	0.58	0.98	0.02
	360min	2.58	<0.005	0.33	0.52	0.44	>0.25
	720max	3.94	<0.005	0.39	0.37	0.60	0.15
	720min	2.39	<0.005	0.23	0.82	0.30	>0.25
Time to Failure (h)		3.91	<0.005	0.54	0.16	0.50	0.23
Coherence		0.52	0.19	2.10	<0.005	1.16	0.01

Table 2. Mean, Standard Deviation, Relative Minimum, and Relative Maximum values.

Parameter		Distribution	Mean	Std. Dev.	Rel. Min	Rel. Max
Linear Time (h)		Lognormal	250:20:16	104:30:21	114:01:04	163:10:56
Velocity Linear (mm/h)		Lognormal	0.87	1.03	0.86	4.63
Progressive Velocity (mm/h)	60min	Gamma	1.45	1.73	1.44	3.06
	60max	Gamma	15.78	71.37	15.18	12.42
	180min	Gamma	1.19	1.15	1.15	2.22
	180max	Lognormal	9.25	4.34	7.24	8.66
	360min	Gamma	1.08	0.94	1.07	1.91
	360max	Lognormal	6.15	3.23	4.95	7.16
	720min	Gamma	1.06	1.00	1.05	2.00
	720max	Lognormal	4.22	2.45	3.49	4.64
Inverse Velocity (h/mm)	60max	Gamma	1.04	0.53	0.96	2.54
	60min	Lognormal	0.08	0.11	0.06	0.06
	180max	Lognormal	1.69	1.42	1.57	6.00
	180min	Lognormal	0.15	0.18	0.12	0.09
	360max	Lognormal	1.87	1.54	1.73	4.38
	360min	Lognormal	0.24	0.26	0.20	0.25
	720max	Lognormal	2.11	1.85	2.07	5.81
	720min	Lognormal	0.37	0.37	0.31	0.35
Time to Failure (h)		Gamma	8:21:47	1:42:55	7:41:28	30:05:05
Coherence		Normal	0.41	0.22	0.38	0.57

B. Empirical Model

Summarize the data in Table 2, below is the empirical model of rock slope behaviour in this study (Fig. 3). Velocities and inverse velocities value that are mentioned in this description use 60 minutes of calculation period since this VCP is the most used in failure back analysis. The rock instability starts with linear deformation trend for about 10 days, 10 hours, and 20 minutes until the onset of failure with an average velocity of around 0.87 mm/h. The velocity started to increase from 1.45 mm/h. The progressive state takes around 8 hours and 22 minutes before failure occurs, with maximum velocity of around 15.78 mm/h. The failure pattern has 0.41 coherence value and a minimum inverse velocity of around 0.08 h/mm. This model later could be used as consideration in taking decisions or setting up an alarm.

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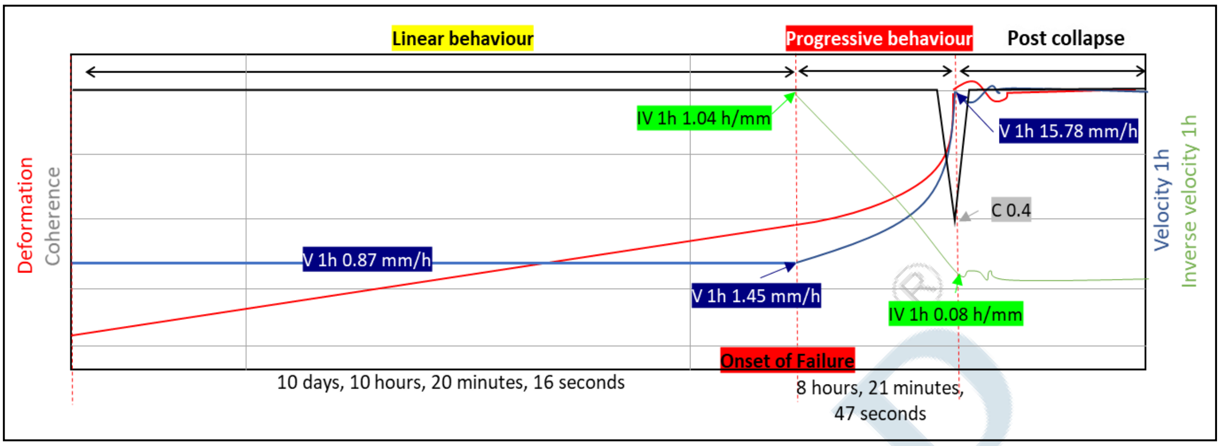

Fig. 3: Empirical rock behaviour model from statistic data.

Different calculation period for velocity could be a better option in setting the alarm threshold as it has lesser noise compared with that of VCP60. The longer the calculation period used, the smaller the velocity value we will have. By using VCP180 minutes, the velocity increased from 1.19 mm/h to 9.25 mm/h with minimum inverse velocity of 0.15 h/mm. In VCP360 minutes, the increased velocity is from 1.08 mm/h to 6.15 mm/h with minimum inverse velocity 0.24 h/mm. And when the VCP720 minutes is used, the increased velocity is from 1.06 mm/h to 4.22 mm/h with minimum inverse velocity 0.37 h/m.

IV. CASE STUDY

Below is one of the rock slope failures that occurred on September 19th, 2022. This model has a resemblance to the empirical model as described below. The linear started at 12:02 PM September 14th, 2022 until on-set of failure at 6:25 AM September 19th, 2022. It lasted for around 4 days, 8 hours, and 23 minutes with average velocity of about 0.91 mm/h. Then, the velocity increased from 0.9 mm/h to 14.57 m/h in about 8 hours and 43 minutes. The failure occurred at 15:03 September 19, 2022, with minimum inverse velocity of 0.07 and coherence value of around 0.56 (Fig. 4).

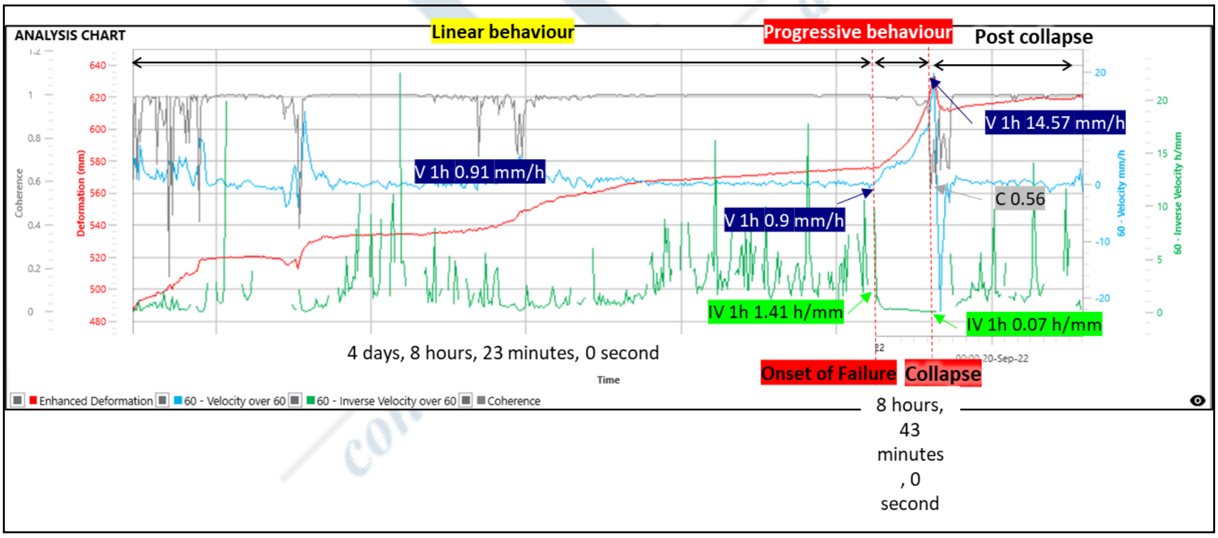

Fig. 4: Back analysis of failure that occurred on September 19th. 2022.

V. CONCLUSION

Based on Anderson-Darling fitting test, the result shows that both linear time and velocity linear have the best fit with the lognormal distribution. In the progressive state, most of the velocity datasets have tendencies to follow the gamma distribution, however, most of the inverse velocities data are best fitted with the lognormal distribution. Time-to-failure data also has the best fit with the gamma distribution and the coherence dataset is the only one that has a normal distribution.

The empirical model started with linear deformation trend with average velocity 0.87 mm/h that take 10 days, 10 hours, and 20 minutes. The progressive state takes around 8 hours and 22 minutes with increasing velocity from 1.45 mm/h to 15.78 mm/h (VCP60). The failure pattern will have 0.41 coherence value and minimum inverse velocity around 0.08 h/mm (VCP60).

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