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Application of Gutenberg-Richter Relation in AE Data Processing

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Abstract: Gutenberg-Richter relation is used for obtaining the relationships of earthquake number with different magnitudes. The regression result, b value, represents the ratio of earthquake numbers. The lower value means the frequently occurrence of larger earthquakes and mainly distributed in seismic zones and high geo-stress areas. Acoustic Emission(AE) is the energy releasing during loading or fracturing process of materials. It acts like a transient wave which is similar to the seismic waves. In this study, G-R relation is revised and then applied for processing AE data. Two different type sensors were adopted for acquiring high frequency signals of concrete specimen under compression. The regression parameter, b_A value, was discussed for different loading levels and the integrity of materials. The primary results show good linear relation between logarithm of amplitudes and appearing numbers. For larger amplitude range, b_A value is around 2.5 during the whole loading process. It means this value is dependent with loading levels and fracturing of materials and also unchanged with different acquisition and processing parameters. This value could properly reflect the property of AE events. For lower amplitude range, b_A value varies with increasing loading. The variation is not obvious for medium loading level. At high loading level, b_A value decreases significantly. It suddenly drops beneath 1 at the failure of specimen. This variation is the same for records with different sensors. For AE monitoring, this value could be used for predict the failure of materials.

Keywords: AE, Concrete, b value, Loading, Sensor

1. Introduction

The energy releasing during the loading process of concrete material emits outward as a transient wave and called as AE event. These events were verified to be related to the condition of loading or integrity of materials. So the observers could collect and process AE events for assessing the fracturing process of materials. Such transient waves are often with high dominant frequency, it means the data amount is enormous. The counting methods, including count rate and cumulative count, are often adopted for simplifying and quantifying the digital record. Furthermore, the threshold should be adequately introduced for filtering the noise and the statistics results could reflect the activities of AE events.

Watanabe et al. [1] discussed AE events of concrete specimens under compression. The count rate was ranged from 200 to 600 when the specimen was cracking and fracturing. Similar tests were also conducted by Ko and Yu [2]. The obvious count rate could reach 80,000. Besides, the count rate of tension failure of concrete beam specimen was

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around 15,000. Katsaga et al. [3] adopted multi-channels AE sensors for locating the crack of RC beam model under loading. In general, the locations of AE sources were consistent with the mapping results of visible cracks. The local maximum count of AE events due to cracking was about several hundreds. Besides the mechanism of cracking, Kaiser effect was revealed with cyclic loading of full scale RC beam model [4]. The significant cumulative count was nearly 60,000. For in-situ test, the application of AE monitoring with pre-stress bridge showed the maximum count was around 40,000 [5]. This high count value could come from the forming of cracks. Golaksi et al. [6] also carried out the similar test with existing bridges, the count was between 20 and 40. The remarkable differences of counting results mentioned above could be mainly attributed to the distinct mechanism of AE events, they are Kaiser Effect, deformation, cracks, et al. [7]. Nevertheless, the different acquisition and processing parameters would also seriously affect the test results. It means the counting results could only reflect the relative variations but absolutely definition of loading levels or material integrity.

These years, the signal processing methods were applied for characterizing AE events. Some preliminary studies showed that some parameters of signals, including the dominant frequency and amplitude, could be related to the fracturing mechanisms. Besides, the empirical equation of seismic waves was also introduced for quantifying AE data and correlated with the integrity of materials.

2. Gutenberg-Richter Relation

Eq.1 shows Gutenberg-Richter relation, M is the magnitude of earthquake and N is the earthquake number with finite magnitude interval (larger than M), both a and b are the regression parameters.

$$\mathrm{Log}\,[N] = a - b\,M \tag{1}$$

From the view of probability, theoretical b value is equal to 1[8]. In practice, many applications showed the calculated b values were deviated from 1. It could be due to the restricted and limitation of observations in time and space. In general, the areas with frequent seismic activities and high geo-stress showed lower b values [9]. In Taiwan area, b values are between 0.5 and 1 and lower for the seismic zones [10]. In general, b values are lower for the seismic zones of the world, the average is around 1 [11].

Colombo et al. [12] revised this relation and applied in AE data. The loading test of concrete beam model showed b values are mainly between 0.5 and 2 and decreased as the appearing of cracks. Shiotani et al. [13] improved G-R relation and defined Ib value. Watanabe et al. [1] applied this new definition and found Ib values were mainly between 0.08 and 0.1 during the loading process of concrete specimen. It decreased to 0.05 as the appearing of cracks. Shiotani et al. [14] conducted in-situ tests of bridge structures. The test results showed Ib values were between 0.06 and 0.1 for sound structures and 0.05 for fractured structures. The above researches show that both b values and Ib values could reflect the loading conditions or the integrity of concrete material.

AE event emits from the fracturing of concrete material under loading. With monitoring data, the origin time and location of source could be estimated. The mechanism of such event is similar to earthquake, so G-R relation is also suitable for processing AE data. While numerous events emerge successively at high loading levels and often result in the overlapping of meaningful signals. Furthermore, the channel number of observations is limited. In practical, there is no enough information for determining the magnitude of individual AE source. G-R relation could not be introduced for processing AE data directly.

The logarithm of amplitude of seismic wave is in proportional to the magnitude in definition of Richter magnitude. This research replaced magnitude in Eq. 1 with the logarithm of amplitude, see Eq. 2, for processing AE data.

$$\text{Log}\,(N_A) = a_A - b_A\,\text{Log}\,(A) \quad (2)$$

N_A value is the number of wave crests with finite time window at specific amplitude (A). Both a_A and b_A are regression parameters.

This relation was applied for AE data which was acquired from the loading test of concrete specimen. The regression parameter, b_A, was discussed with different acquisition and processing parameters also the loading levels and the integrity of specimen.

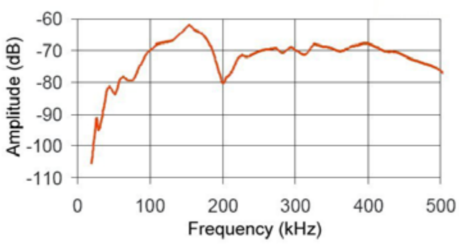
3. Compression Test and AE Record

The cylindrical concrete specimen was used for monotonic compression test, see Photo 1. The designed strength of sample was 350 kgf/cm^2, the height was 30 cm and the diameter was 15 cm. Stress control was adopted for compression test, the loading rate was 450 kgf/sec. Two rubber plates were installed properly on both sides of specimen for reducing the impacting of loading machine. After the loading was applied, there were no obvious cracks on the specimen for the most time. Eventually the loading was terminated due to the local fracturing of specimen. Additional to some cracks, the specimen was still keeping intact. The failure strength was 413 kgf/cm^2, a little higher than designed value.

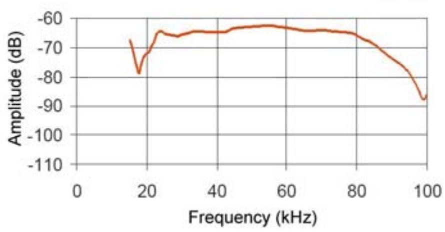
Photo 1. Layout of Compression Test

Two sensors were adopted for sensing AE events. Digital data was continuously recording with 800 kHz sampling frequency and 100 mV input voltage, voltage resolution was set to 0.003 mV. Figure 1 shows the frequency response of both sensors. First type is resonant sensor, VS-150, with 150 kHz central frequency. Accompanying with suitable pre-amplifier, the meaningful frequency range of digital record is from 20 kHz to 400 kHz. Second type is broad band sensor, VS-30. The effective frequency range is form 2 kHz to 400 kHz.

Before loading, the noise test showed two distinct features. They were characterized as white noise and 60 Hz AC. The voltage oscillated quickly with a slow relief while the range of variations was not obvious. The maximum voltage was 0.03 mV for VS-150 record and 0.06 mV for VS-30 record.



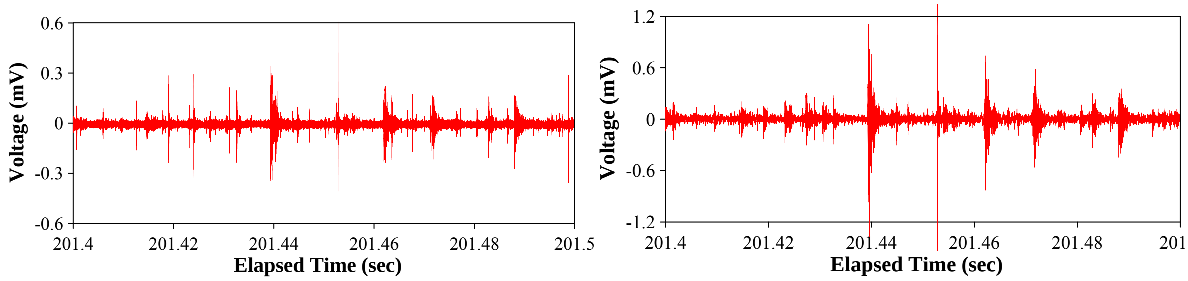
[a] VS-150 Sensor



[b] VS-30 Sensor

Figure 1. Response Curve of AE Sensors

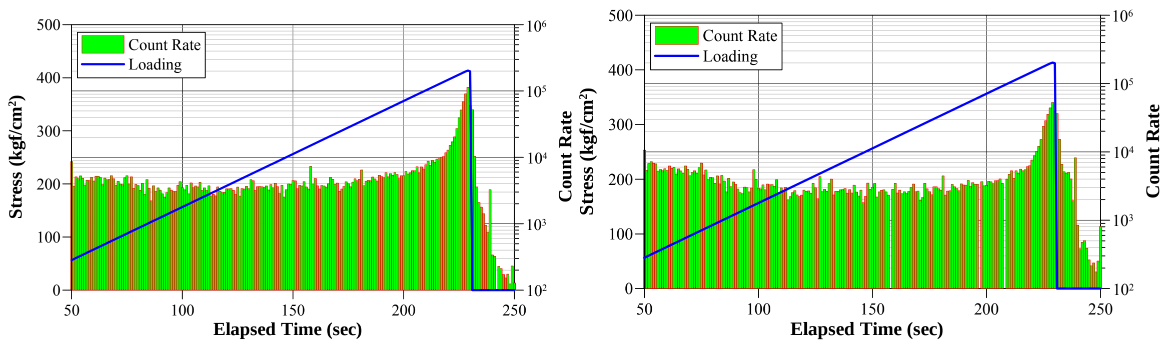
Figure 2 shows two AE records, which were extracted from the original records at 350 kgf/cm^2 with 0.1 second time window. Both records show many AE events, over 20 events could be identified and confirmed. However, more signals are interfered mutually and could not be identified. It means some important parameters of AE event, such as rise time, peak amplitude and duration, could not be obtained. Besides, it is not easy to distinguish the sequential of events in both records. These limitations would largely restrict the processing and quantifying of each event, not to mention the estimating of origin time and locating of source.



(a) VS-150 Record (b) VS-30 Record

Figure 2. AE Records

Due to enormous amount of AE data, analysis of record by event is impractical and the statistics method is thus a suitable alternative way. Figure 3 shows the histories of loading and count rate. Count rate is the number of wave crests in one second. The maximum noise voltage of each record was adopted as threshold for filtering the noise. The results show two local maximums. The first one is appearing at the beginning of loading, it is the effect of contact between loading machine and the specimen. At the end of loading test, the extreme is over 100,000 for VS-150 record and around 55,000 for VS-30 record. It reflects the failure of specimen. Besides, the variation is not obvious for low to medium loading level, count rate is around several thousands.



(a) VS-150 Data (b) VS-30 Data

Figure 3. Histories of Loading and Count Rate

The fracturing process of concrete material under loading could be categorized as three stages. They are the forming of microcracks, appearing of visible macrocrakcs and eventual rupturing[15]. The moderate value of count rate could be interpreted as the appearing of microcracks. Larger value could be considered as the effect of major cracks and failure of specimen. The relative variation of statistics results could be used for assessing the integrity of specimen. Nevertheless, count rate is different at each moment for both records. The single value is meaningless and could not be related to the loading levels and the fracturing of materials.

The dominant frequency of VS-150 record is greater than that of VS-30 record. It means the wave number is larger for VS-150 record naturally. This hardware property is more obvious when numerous AE events appearing and could be reflected with count rate.

4. Analysis Results of AE Records

4.1 Property of N_A Value

Eq.2 was applied for processing AE records. For the digital record with fixed sampling rate, there is exiting some upper bound for counting the number of amplitude. Besides, AE events with high energy could be distorted due to the limited input voltage. The number of high amplitude signals could less than the real condition. It means the statistics results could be affected with acquisition parameters. Figure 4 shows the distribution of statistics results. The horizontal axis is amplitude(A), the unit is voltage. The vertical axis is appearing number(N_A). Two datasets were for different statistic parameters and extracted from VS-150 record at stress of 412kgf/cm^2 with one second time window. For case-1, N_A is the number of wave crests for amplitude higher than specific voltage(A). For case-2, N_A is the summation for specific voltage interval[A-ΔA~A]. The specific voltage is multiple of 0.02 mV the increment(ΔA) is 0.02 mV.

In general, N_A values decrease accordingly with increasing voltage while consistently larger for case-1. It implies that the predominant of cumulative number over count rate. Between 0.1 mV and 1 mV, the distribution shows good linear relation, b_A values are 1.73 and 2.53 respectively.

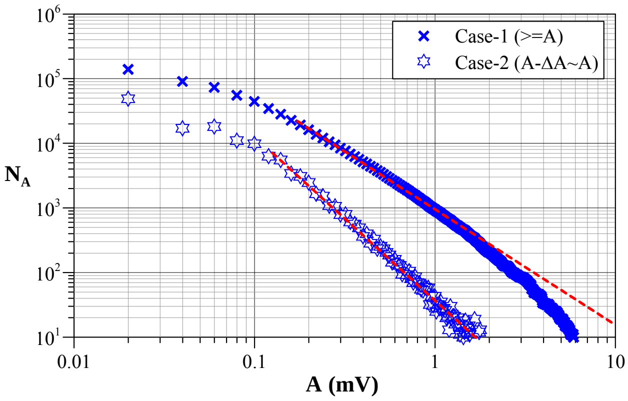
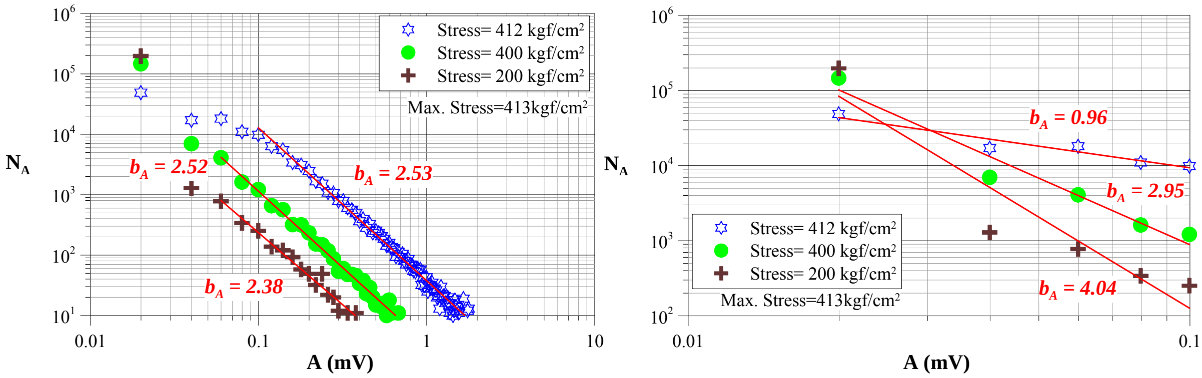


Figure 4: Distribution of N_A Value

For voltage less than 0.1mV, N_A values are relative lower for both cases. It could be due to the emergence of enormous AE events. The moderate signals occupy the record and the ratio of low amplitude signals was thus reduced. For case-1, N_A values also show relative lower for voltage higher than 2mV. It could be the effect of distortion of signals with high amplitude. But the main reason is the small amount of high energy AE events. This research adopted the parameters of case-2 for processing the records at different loading levels for b_A values.

4.2 Property of b_A Value

Figure 5 shows the statistics results at three loading levels with VS-150 record. In general, N_A values increase with increasing loading. Three datasets show similar linear relation. For high voltage range, b_A values are between 2.38 and 2.53, the average is around 2.5. It means the value is nearly independent with loading. For low voltage range, N_A value at 0.02 mV is about 200,000. It stays unchanged before cracking of specimen, the stress is less than 400 kgf/cm^2. It obviously reduces to 50,000 at stress of 412 kgf/cm^2. N_A values at higher specific voltage increase identically with increasing loading. Generally, for low voltage range, b_A values decrease with increasing loading. It drops from 4.04 to 0.96, the variation is over 70%.



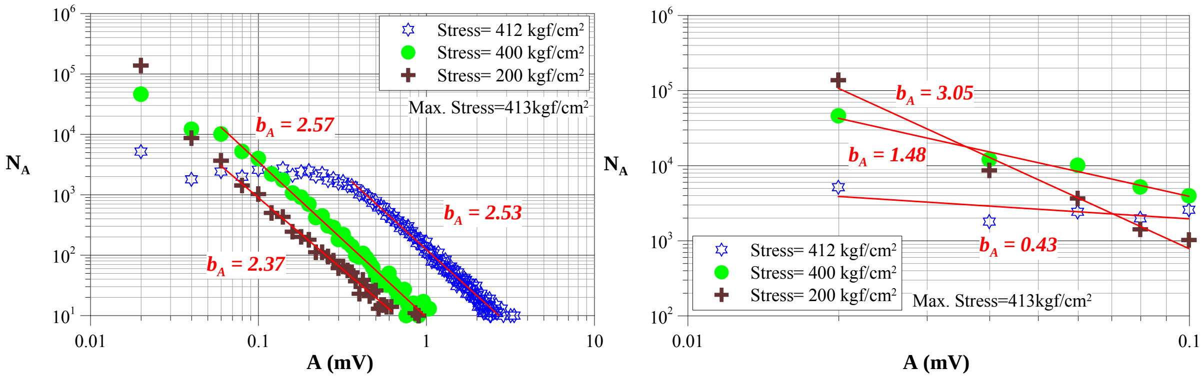
[a] Full Voltage Range [b] Low Voltage Range

Figure 5. b_A Values at Different Loading Levels(1)

Figure 6 is the analysis results of VS-30 record. N_A values of three datasets increase with increasing loading and higher than that of VS-150 data. The linear distribution for high voltage range is also obvious for these data, b_A values are 2.37, 2.49 and 2.57 respectively. These values are close to that of Figure 5(a). For low voltage range, b_A values are 3.05, 1.48 and 0.43 respectively. They are little lower than that of Figure 5(b), while also decrease identically with increasing loading.

4.3 Sensitivity Study of Statistics Parameters

For understanding the influence of statistics processing with b_A value, the different parameters were adopted for compare. Two voltage increments(ΔA) are 0.03 mV and 0.05 mV respectively, both time windows are 0.1 second and 1 second. The combinations of parameters were applied for processing the records at stress of 412 kgf/cm^2



(a) Full Voltage Range (b) Low Voltage Range

Figure 6. b_A Values at Different Loading Levels(2)

Figure 7 shows results of six datasets. In general, N_A values are greater both with larger parameters and for VS-30 record. Meanwhile, N_A values decrease accordingly with increasing voltage, b_A values are ranged from 2.56 to
2.61 and the average is about 2.6. This results shows b_A value would not vary with different

statistics parameters. It reveals the value could reflect the property of AE events.

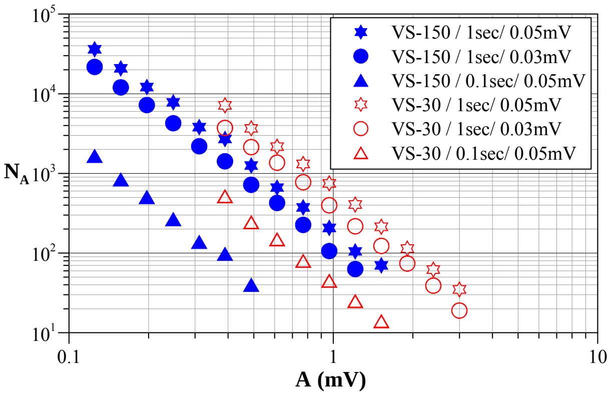


Figure 7. Comparisons of Different Statistics Parameters

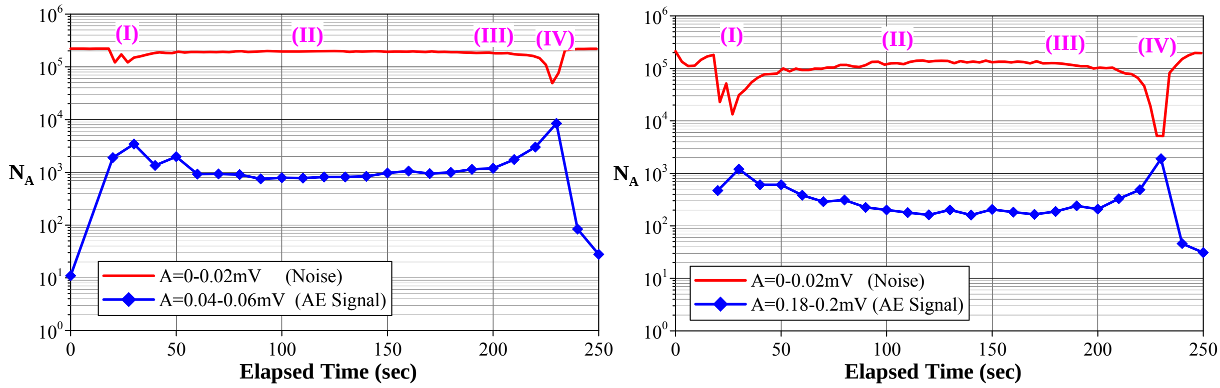
4.4 Time Variation of N_A Value

Figure 8 shows the time variation of N_A values at two specific voltages. The voltage of noise is less than 0.03 mV for VS-150 record, so N_A values at 0.02 mV could roughly reflect the property of noise. The sampling rate is 800 kHz for digital record, it means the maximum peak number in one second is 400,000 for continuous oscillation of voltage. Furthermore, 60 Hz AC would influence the record and result in the slight relief of waveform. In general, there are about 200,000 peaks locating in positive voltage. N_A value of minimum voltage in Figure 8(a) is 220,000 before loading which is similar to the theory value. The loading is applied at 20th second, labelled with "(I)" in plots. In this stage, N_A value decreases to 120,000 and returns 180,000 instantly. For consistent loading stage, labelled with "(II)" in plots, N_A value stays around 180,000 and almost unchanged. For latter stage, labelled with "(III)" in plots, N_A value slightly decreases with cumulative loading. At final stage, labelled with "(IV)" in plots, N_A value significantly lowers down in short time. The distribution of N_A value of larger voltage shows distinct trend with elapsed time. For stage "(I)", N_A value raises up locally. For stage "(II)", N_A value stayed unchanged with cumulative loading. For stage "(III)", N_A value slightly increases with loading. For stage "(IV)", N_A value significantly increases in short time. For VS-30 record, N_A values of different voltage could also be categorized as four stages with elapsed time. The distributions could also reflect the properties of noise and AE signals respectively.

The analysis results mentioned could be concluded as follows. The contact of loading machine and specimen at beginning of test would produce some meaningful AE events due the effect of impact and friction. N_A value of larger voltage increases locally. When the loading is consistently increasing, N_A value of larger voltage sustains at moderate level. It could be due to the continuous deformation and forming of microcrakcs of specimen during loading. When the loading is approaching the strength of specimen, the cracks emerge successively and enormously which would result in the remarkable N_A value. Moreover, the noise would be covered for those high energy signals which would largely reduce N_A value of minimum voltage at final stage.

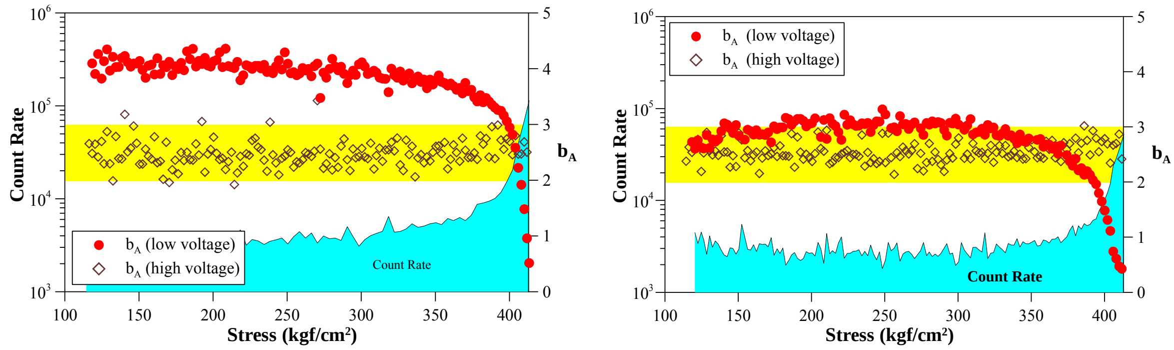
4.5 Count Rate and b_A value with Loading

Figure 9 Shows count rate and b_A value with loading. The diamond symbols in plot are $b_A$values for high voltage range. The values are mainly between 2 and 3, the average is about 2.5. It is independent with the sensor type and loading level. For low voltage range, b_A values stay unchanged in low to medium loading level and are around 4 for VS-150 data. The values are somewhat lower for VS-30 data but also stay fixed with increasing loading. In high loading level, b_A values decrease accordingly and quickly with increasing loading. At the failure of specimen, b_A values of both data drop and beneath 1. In the mean time, the count rate of both records reaches the maximum value while the value of VS-150 record is nearly multiple of VS-30 record.



(a) VS-150 Data (b) VS-30 Data

Figure 8: Histories of N_A Values



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5. Conclusion

This study revised Gutenberg-Richter relation, replaced the magnitude with logarithm of amplitude, and applied with AE data. The primary results show linear relationship between appearing number and amplitude. In addition, the linear distribution is the same for records with different sensors and statistics parameters. The conclusions could be summarized as follows.

1. The logarithm of appearing number is in reverse proportional to the amplitude. For high amplitude, the regression analysis shows b_A value is about 2.5 and independent with the data acquisition and processing parameters, loading levels and the integrity of concrete materials. This value would properly reflect the property

of AE events.

2. After loading, the meaningful AE events emerge and cover the low voltage noise on the records. The records are dominated with higher voltage signals and thus the appearing number of low voltage signals is suppressed. For lower voltage range, b_A value means the ratio of meaningful signals to noise. It varies significantly at the beginning of loading. Though the loading is increasing constantly, it converges then stays unchanged in low to medium loading level and is consistently higher for VS-150 record.
3. As the loading is approaching the strength of specimen, b_A value decreases quickly. It drops and beneath 1 at failure of specimen. The variation is the same for both records with different sensors. This value would properly reflect the integrity condition of concrete material.

Reference

[1] Watanabe T., Nishibata S., Hashimoto C. and Ohtsu M. 2007. Compressive Failure in Concrete of Recycled Aggregate by Acoustic Emission, *Journal of Construction and Building Materials*, 21: 470-476

[2] Ko, W. C., and Yu, C. W. 2008. Monitoring the Fracture Process of Concrete Specimens with AE System, *Proceedings of 3rd International Symposium on Advanced Fluid/Solid Science and Technology in Experimental Mechanics*, Tainan, Taiwan

[3] Katsaga, T. Sherwood, E. G. Collins, M. P. R., and Young, P. 2007. Acoustic Emission Imaging of Shear Failure in Large Reinforced Concrete Structures, *International Journal of Fracture*, 148: 29-45

[4] Šajna A. and Bremec T. 2008. Acoustic Emission Technique based Investigation of Old Bridge Girders, *Proceedings of IAES*-19: 317-324, Kyoto, Japan

[5] Yuyama, S., Yokoyama, K., Niitani, K., Ohtsu, M., and Uotomo, T. 2007. Detection and Evaluation of Failure in High-Strength Tendon of Prestressed Concrete Bridges by Acoustic Emission, *Journal of Construction and Building Materials*,21 : 491-500

[6] Golaski, L., Gebski, P. K. Ono 2002. Diagnostics of Reinforced Concrete Bridges by Acoustic Emission, *Journal of Acoustic Emission* 20: 83-98

[7] Ko, W. C., and Yu, C. W. 2008. Study of Kaiser Effect in Concrete Material Under Cyclic Loading, *Proceedings of IAES*-19: 295-302, Kyoto, Japan

[8] Karen Felzer 2009. Universality of the Gutenberg-Richter Relationship, USGS website

[9] Huang, J., and Turcotte, D. L. 1988. Fractal Distribution of Stress and Strength and Variations of b-Value, *Earth Planetary Science Letter* 91: 223-230

[10] Chen, D. Y., Chang C. W., and Hsiao N. C., 2009., Applied Gutenberg-Richter Relation to Study the Potential Areas of Large Earthquakes in Taiwan, Proceedings of 2009 *Annual Congress of Chinese Geophysical Society and the Geology Society of Taiwan*: 51

[11] Wu, M. L., 2007. “b Values of Shallow Earthquakes in Taiwan” Master Thesis of Chun-Kun University

[12] Colombo, I. S., Main, I. G., and Forde, M. C. 2003. Assessing Damage of Reinforced Concrete Beam Using b-value Analysis of Acoustic Emission Signals, *Journal of Materials in Civil Engineering*, 15, 3: 280-286

[13] Shiotani, T, Fujii, K., Aoki, T. and Amou, K. 1994. Evaluation of Progressive Failure Using AE Sources and Improved b-Value on Slope Models Tests, *Progress in Acoustic Emission VII, JNSDI*, 7: 529-534

[14] Shiotani, T., Yasuhiro N., Xiu L. and Hiroshi H. 2004. Damage Assessment in Railway Sub-Structures Deteriorated

Using AE Technique, *Proceedings of EWGAE* 2004: 225-232

[15] Barbara, S. and Thomas, V. 2004. Acoustic Emission for Monitoring Damage Accumulation in Reinforced Concrete Structures, *Proceedings of EWGAE* 2004: 107-114