Proposed SDI Equations to Improve the Effectiveness in Evaluating Crack Damage on the Road Pavement

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Proposed SDI equations to improve the effectiveness in evaluating crack damage on the road pavement

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Abstract. Road pavement has a life-cycle, where the age of the road pavement starts from design to the end of service life, so that maintenance works are one of the most important stages. To enable carrying out maintenance works, a process of assessment of road conditions, both from structural and functional, is required. At present, one of the evaluations of the functional condition of the road is using surface distress index/SDI. The SDI method used today has a simple procedure and is easy to use. However, in the term of accuracy in estimating the functional condition, it will be seen that the SDI parameter is far from satisfying. In this study, an effort to increase the effectiveness of SDI parameters especially for crack damage was carried out. The improvement of SDI parameter was conducted by developing a non-linear equation for each type of crack damage based on the deduct value curve of the PCI method, with a coefficient of determination R^2 of at least 0.99. The proposed SDI equations have been calibrated and produced an error less than 6.2%. A comparison between the value of the proposed and the existing SDI also was presented and the results showed that the similarities between the two SDI values were only 19.86%. The rest of the existing SDI value was under- estimate proposed SDI, but there was also an existing SDI value over-estimated proposed SDI, especially in the road segment which was only found one type of crack damage with low/medium severity and low density.

1. Introduction

Road pavement has a repetitive life cycle, starting from planning, construction, operational, maintenance/rehabilitation, reconstruction and then this process returns to the operational stage and so on. Of all these processes, maintenance/rehabilitation (M & R) is a stage that has the longest period compared to the other stages, and together with operational and reconstruction stages, M & R will last until the end of the service life of the road pavement.

To determine the type of maintenance work required, the road agency will conduct a process of evaluating road conditions, to ensure that the proposed maintenance work is appropriate. This is important due to the limit amount of the available budget so that only the most effective and efficient one should be processed. This underlines how important the process of road condition evaluation is. Two kinds of condition evaluation that are usually conducted namely functional and structural condition evaluations.

Functional condition evaluation is performed to find out whether the road pavement still has an adequate level of performance to be able to carry out its functions. This evaluation on a flexible pavement usually consists of 3 types, i.e. evaluation of road deterioration, roughness, and skid

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resistance. In Indonesia, one parameter that is commonly used to evaluate the functional condition of the road is called surface distress index (SDI) [1]. The SDI parameter is very simple and easy to use because it only evaluates 3 types of road damage (i.e. cracking, potholes and ruts), compared to 19 types of road damage identified in PCI (Pavement Condition Index) method [2,3], another parameter that is used to evaluate the road functional condition.

One type of damage in SDI, which is crack damage, is only represented by one type of crack damage compared to seven types of crack damage in the PCI method. With all the features, the PCI method is recognized by AASHTO as one of the most comprehensive methods in estimating the functional condition of the road [4,5,6]. However, with its comprehensive level, the measurement and analysis procedure of the PCI method becomes very complex. In this point of view, the advantages and disadvantages of SDI actually lie. The advantages of the SDI are in terms of simplicity and ease of measurement of the functional condition of the road in practice by surveyors with low to medium education levels, while the weakness of the SDI is the simplification can lead to inaccurate estimation of road functional condition, which in turn will affect the inaccuracy in the selection of road handling types.

This research is an initial part of a series of studies that aims to optimize the use of SDI parameters for the purpose of evaluating the functional condition of the road. As an initial stage, this research is intended to propose an increase in the effectiveness of SDI parameters especially for evaluating the crack damage on the road pavement.

2. Surface Distress Index (SDI)

Surface distress index (SDI) is a scale of road functional condition obtained from visual observations (road condition survey/RCS) and detailed measurements on road damage that occurs in the field. In observing road damage in the field, the road evaluated has to be divided into 100 m long segments based on the Road Condition Survey (RCS) Guide No. SMD-03/RCS [1]. According to this guide, there are 4 criteria for determining the SDI index, namely the total area of the crack, the average crack width, the number of holes per km of road length, and the average rut depth. Especially for crack damage, the SDI equations for this kind of damage are as follows.

- SDI_1 as a function of total area of crack

$$\begin{aligned} SDI_1 &= 5 && \text{if total area of crack is less than 10\%} \\ SDI_1 &= 20 && \text{if total area of crack is in between 10\% and 30\%} \\ SDI_1 &= 40 && \text{if total area of crack is more than 30\%} \end{aligned} \quad (1)$$

- SDI_2 as a function of average crack width and SDI_1

$$\begin{aligned} SDI_2 &= SDI_1 && \text{if average crack width is less than 3 mm} \\ SDI_2 &= SDI_1 * 2 && \text{if average crack width is more than 3 mm} \end{aligned} \quad (2)$$

According to the equations above, the maximum SDI value for the criteria of total area of crack and average crack width equals to 80. SDI parameter has main advantages in the form of simplicity and ease of use, but this parameter has several fundamental weaknesses, namely:

a. There is only one type of crack damage, although in practice crack damage has more than one type with various characteristics;
b. All the results of SDI parameter analysis are discrete (not continuous) so the results of different damage measurements can get the same SDI value

3. Research Methodology

This research consisted of three main stages as follows.

- Collection of data related to damage. The types of data needed in this study include the type of crack damage, dimensions of crack damage (expressed as the ratio between the extent of damage to the area evaluated or named as density in %), and the severity of the crack damage.

Variations of the data refer to the PCI method [2, 3], i.e. there are 7 types of crack damage and 3 damage severity levels. The data is collected using road condition survey (RCS) method developed by Setiadji et al. [7]. There are 9 RCS locations, which is consisting of urban, provincial and national roads. Seven of nine RCS locations around Semarang is shown in figure 1, while two other locations, that is, Bawen - Salatiga road and the Weleri - Temanggung road, are at a considerable distance from Semarang city.

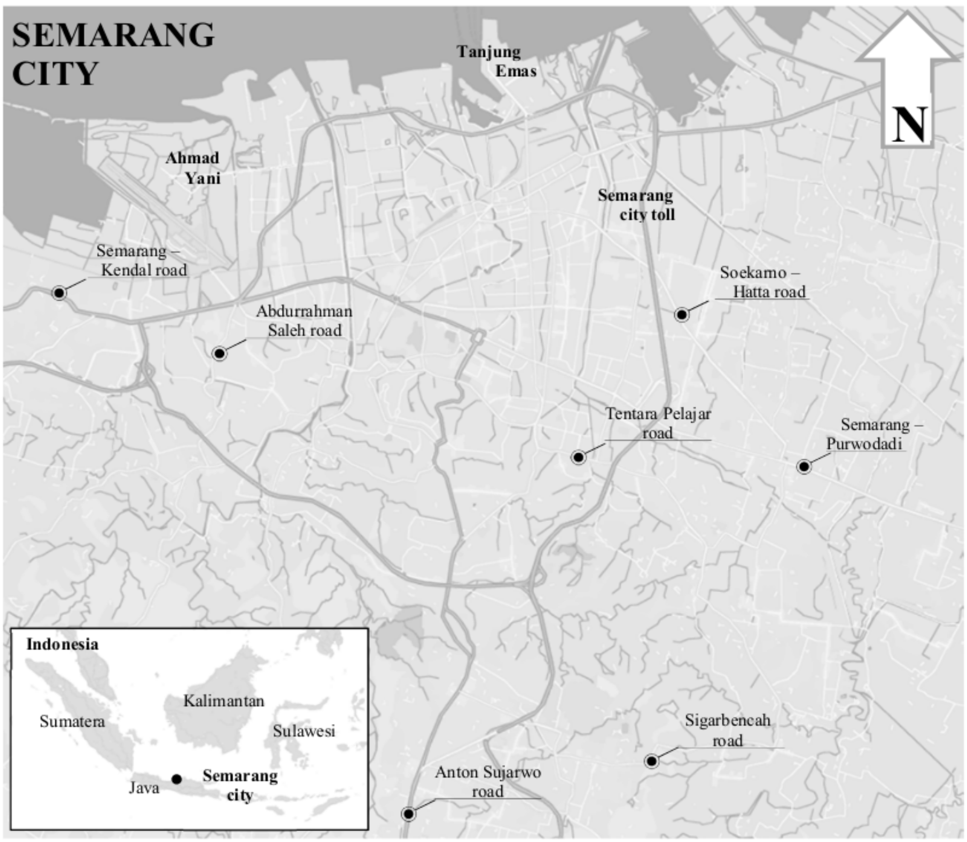

Figure 1. Locations of road condition survey around Semarang city

- Development of the proposed SDI equations. As a reference for developing the equations, PCI method were used. In PCI method, there are 2 steps of determining PCI values: (i) to score on the negative effects generated by each type of distress based on distress density and level of severity, called as deduct value; (2) to calculate PCI value where the summation of deduct values produced by different distresses will be used to subtract from possible maximum PCI, i.e. 100 [8]. In step (2), it is possible to make adjustments to the total deduct value so that the calculated PCI is not negative. In this study, only step (1) of the PCI method was adopted for the development of proposed SDI value. Step (1) of the PCI method is similar to the determination of the SDI value, where distress density and level of severity variables (see Fig. 2), are similar to the SDI_1 and SDI_2 variables (equations 1 and 2) in the SDI method. In this part, the SDI_1 variable, which has a discrete value, needs to be improved by adopting the density variable from the PCI method which has a continuous characteristic. According to this similarity, the proposed SDI values can be assumed as a function of the deduct value curves. However, the total score of deduct value in the PCI method is different from the total score of the damage of the SDI method, which is a maximum of 100 and 80 respectively. Therefore, it is necessary to adjust the total score of deduct value so that the total score can be used in the SDI method.

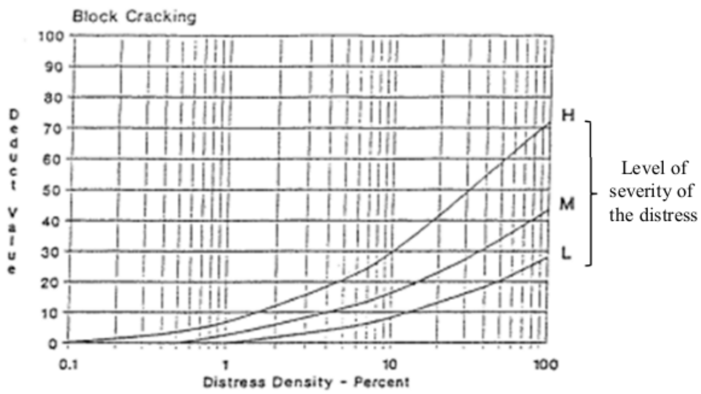

Figure 2. Example of deduct value curve in PCI method [2, 3]

In order to allow the proposed SDI value is still usable in RCS Guide [1], the maximum existing SDI value was adopted. Adjustment of the proposed maximum SDI value for the crack damage to the total proposed maximum SDI value (taking into account pothole and rut damages) will be carried out at the next stage of this research.

- The use of the proposed SDI equations to evaluate the functional condition of the road by using data collected in stage 1. Subsequent analysis was carried out by comparing the existing and proposed SDI values from the equations developed to see the effectiveness of the use of the proposed SDI values to assess the functional condition of the road.

4. Results and Discussion

The most important step in this study was to develop the proposed SDI equations. As explained in section 3 previously, the deduct value (DV) curve of seven types of crack damage in the PCI method was used to develop the proposed SDI equations. Each DV curve has 3 levels of severity, i.e. high, medium and low, and each level of severity has a different density range. A density range of up to 100% can be found on the DV curve of alligator cracking, block cracking and slippage cracking. As for other types of damage, the density range varies between 0 - 30%.

Using hypothetical data from the density parameters, DV values will be obtained for each severity level, where the DV values obtained will form the following sequence: $DV_{low\ severity} < DV_{medium\ severity} < DV_{high\ severity}$. Based on the DV value of each density, the SDI value can be calculated using the following equation.

$$SDI = 80 * DV / DV_{max} \quad (3)$$

In which: 80 is the maximum SDI value for crack damage, DV is the deduct value for each density, DV_{max} is the maximum DV value for crack damage, i.e., in this case, DV, it is equal to 91 in alligator cracking or slippage cracking damage. The proposed SDI equations developed using equation (3) is as presented in table 1. The SDI equations in table 1 are the improvement of the SDI curves that have been developed by Setiadji et al. [7].

From table 1, except for edge cracking, the SDI equations for all types of crack damage is divided into two, namely the SDI equation for density between 0% - 10% and the SDI equation for the density of more than 10%. This is because it is difficult to model SDI in one equation for all range of density values. By making the SDI equation based on two ranges of density values, all equations in table 1 can have a minimum coefficient of determination (R2) equals to 0.99. Due to a large number of SDI equations produced, to make it easier for ones to use the SDI equation, development of an application based on the proposed SDI equations, called e-SDI, will be initiated at the next stage of research.

Table 1. Proposed SDI equations

Crack types[a] - level of severity[b]	SDI equations for $0 < x < 10$[c]	SDI equations for $x \geq 10\%$
AC – L	$y = 0,0675x^3 - 1,3606x^2 + 9,6465x + 1,0849$	$y = 5E\text{-}05x^3 - 0,0118x^2 + 1,021x + 19,8$
AC – M	$y = 0,1819x^3 - 3,1301x^2 + 16,706x + 5,3688$	$y = 5E\text{-}05x^3 - 0,0118x^2 + 1,0225x + 32,465$
AC – H	$y = 0,2086x^3 - 3,6735x^2 + 20,365x + 9,6453$	$y = 11,154\ln(x) + 28,859$
BC – L	$y = -0,0186x^3 + 0,2614x^2 + 0,0422x - 0,0212$	$y = 2E\text{-}05x^3 - 0,005x^2 + 0,4878x + 3,6144$
BC – M	$y = -0,0171x^3 + 0,1596x^2 + 1,6502x - 0,4228$	$y = 1E\text{-}05x^3 - 0,0043x^2 + 0,5773x + 9,8729$
BC – H	$y = 0,0622x^3 - 1,1344x^2 + 7,8845x - 1,2327$	$y = 5E\text{-}05x^3 - 0,0126x^2 + 1,2512x + 15,333$
LC/TC – L	$y = -0,0051x^3 - 0,0052x^2 + 2,1948x - 0,5303$	$y = -0,0088x^2 + 0,8352x + 8,3516$
LC/TC – M	$y = -0,2536x^2 + 5,1317x + 1,0612$	$y = -0,0176x^2 + 1,3187x + 15,824$
LC/TC - H	$y = -0,4332x^2 + 9,1908x + 5,652$	$y = -0,044x^2 + 2,9011x + 29,89$
EC – L	y = 0,0062x3 - 0,2136x2 + 2,4256x + 0,5135	
EC – M	$y = 0,0072x^3 - 0,2749x^2 + 3,6453x + 3,9194$	
EC – H	$y = 0,009x^3 - 0,3785x^2 + 5,5896x + 7,1162$	
JRC – L	$y = 0,0251x^3 - 0,4627x^2 + 3,5049x - 0,7364$	$y = -0,0044x^2 + 0,6593x + 7,033$
JRC – M	$y = 0,0674x^3 - 1,188x^2 + 7,9693x + 0,7459$	$y = -0,0308x^2 + 1,5824x + 16,264$
JRC – H	$y = 0,1135x^3 - 2,0996x^2 + 14,797x + 2,073$	$y = -0,0352x^2 + 1,8901x + 38,242$
SC – L	$y = 0,0333x^3 - 0,646x^2 + 5,6258x - 0,3221$	$y = 3E\text{-}05x^3 - 0,0092x^2 + 0,8766x + 16,346$
SC – M	$y = 0,0596x^3 - 1,2003x^2 + 9,6815x + 1,3868$	$y = 7E\text{-}05x^3 - 0,014x^2 + 1,073x + 29,157$
SC – H	$y = 0,1087x^3 - 2,1719x^2 + 16,55x + 2,7742$	$y = 7E\text{-}05x^3 - 0,014x^2 + 1,0328x + 51,234$

[a] AC = alligator cracking, BC = block cracking, LC = longitudinal cracking, TC = transversal cracking, EC = edge cracking, JRC = joint reflection cracking, SC = slippage cracking
[b] L = low severity, M = medium severity, H = high severity
[c] x = density (%), y = SDI

Furthermore, a calibration process was necessary to be performed to ensure that the accuracy of the equations before the equations are used in practice. The calibration process was done by comparing two SDI values, i.e. the SDI value obtained from the conversion of DV and SDI values generated by the SDI equations in table 1. The results of the SDI equation calibration process are presented in table 2.

From table 1, it can be seen that all equations can predict the SDI values with a difference of less than 5 points (6.2%). This shows that the proposed SDI equations can estimate all SDI values quite accurately. In addition, the following guidelines are required for the use of the equations in practice.

a) Determine the density value (i.e. the ratio of the area of damage to the area evaluated) for each type of crack damage that is obtained from the results of road condition survey (RCS);
b) The maximum density value of edge crack, joint reflection crack, and longitudinal/transversal cracks are 20%, 30%, and 30%., respectively. For the other types of cracks, the maximum density is 100%;
c) Each type of crack damage with different severity will produce individual SDI values. The individual SDI values of each crack damage and severity level will be accumulated as the total SDI value for the road segment reviewed;
d) If the total SDI value is greater than 80, then the value used is 80. This is because, at this time, the maximum SDI value for crack damage is 80. However, if the total of SDI value is less from 80, then that value is expressed as the total SDI value for the segment.

Table 2. The calibration results for SDI equations

Crack types – level of severity	Average deviation of SDI	Largest deviation of SDI
AC – L	0.67	2.12
AC – M	0.63	2.74
AC – H	0.68	1.72
BC – L	0.27	1.34
BC – M	0.88	3.08
BC – H	0.51	2.04
LC/TC – L	0.12	0.41
LC/TC – M	0.75	1.97
LC/TC – H	0.71	2.29
EC – L	0.23	0.75
EC – M	0.24	0.62
EC – H	0.25	0.85
JRC – L	0.11	0.39
JRC – M	0.34	0.83
JRC – H	0.41	1.77
SC – L	0.71	4.59
SC – M	0.88	4.92
SC – H	0.85	4.51

In the proposed SDI method, each road segment can produce SDI values continuously with more accuracy (not discrete, as indicated by the existing SDI method), where this will be very helpful in doing ranking based on the condition value of the road segment that must be handled. However, because in the SDI method, the total SDI value is a maximum of 80, so that for the road with a value of SDI equals to 80, it indicates that the road is in a condition of severe damage.

To help provide further information on what type of crack damage is dominant, which will be useful in determining the type of handling quickly, it is proposed to provide an abbreviation of the type of crack after the SDI value. For example, if the value of the SDI is 80 AC, it means that the crack damage in that segment is quite significant with the dominant type of crack damage being AC (alligator cracking).

Furthermore, the proposed SDI equations need to be implemented using field data to see the accuracy of this method in predicting SDI values (see tables 3 and 4). In addition, the proposed SDI method will be compared with the existing SDI method to assess effectiveness in delivering information on functional conditions of a road. Table 3 is a comparison of the SDI values produced by the proposed method and the existing method in an urban road, while table 4 presents the same comparison with the road damage data taken on a national road.

Table 3. Comparison between the existing and proposed SDI based on road condition survey on Abdurrahman Saleh Road

Sta.	Crack types[a] & level of severity[b]	Density (%)	Average crack width (mm)	Average crack width per segment (mm)	Total Density (%)	Existing SDI	Proposed SDI per type of crack	Total proposed SDI	Applied proposed SDI
0+100	AC – H	0.96	40	28.33	5.31	10	25.99	63.44	63.44 AC
	AC – M	0.74	30				16.09		
	AC – L	3.61	15				21.35		
0+200	AC – L	1.02	10	22.5	2.83	10	9.58	36.01	36.01 AC
	AC – M	1.81	35				26.43		
0+300	AC – H	0.72	40	40	10.26	40	22.48	98.84	80.00 AC
	AC – M	6.22	30				31.95		
	AC – H	3.32	50				44.40		
0+400	AC – M	3.24	30	17	13.06	40	32.82	94.24	80.00 AC
	AC – L	0.65	10				6.80		
	AC – L	1.62	10				13.43		
	AC – M	3.11	25				32.52		
	LC – L	4.44	10				8.67		
0+500	LC – L	1.67	10	21.67	8.74	10	3.10	34.59	34.59 AC
	BC – L	0.33	35				0.02		
	AC – M	6.74	20				31.47		
0+600	LC – L	0.92	5	5	0.92	10	1.48	1.48	1.48 LC
0+800	AC – L	0.08	10	10	0.63	10	1.85	7.84	7.84 AC
	AC – L	0.55	10				5.99		

[a] AC = alligator cracking, LC = longitudinal cracking
[b] L = low severity, M = medium severity, H = high severity

Table 4. Comparison between the existing and proposed SDI based on road condition survey on Semarang – Purwodadi road (a)

Sta.	Crack types[a] & level of severity[b]	Density (%)	Average crack width (mm)	Average crack width per segment (mm)	Total Density (%)	Existing SDI	Proposed SDI per type of crack	Total proposed SDI	Applied proposed SDI
1+100	LC - L	0.8	10	10	0.8	10	1.22	1.22	1.22 LC
1+200	AC - M	0.61	20	20	0.61	10	14.44	14.44	14.44 AC
1+400	AC - H	1.72	40	40	1.72	10	34.87	34.87	34.87 AC
1+500	AC - M	0.55	20	15	2.52	10	13.64	17.37	17.37 AC
	LC - L	1.97	10				3.73		
1+600	AC - M	0.75	20	20	0.75	10	16.21	16.21	16.21 AC
1+700	AC - M	0.34	15	15	0.34	10	10.69	10.69	10.69 AC
1+900	AC - M	0.43	10	20	1.49	10	11.99	31.76	31.76 AC
	AC - M	1.06	30				19.78		
4+100	AC - M	0.22	20	20	0.22	10	8.89	8.89	8.89 AC
4+400	LC - L	1.41	10	10	1.41	10	2.54	2.54	2.54 LC

Table 4. Comparison between the existing and proposed SDI based on road condition survey on Semarang – Purwodadi road (b)

Sta.	Crack types[a] & level of severity[b]	Density (%)	Average crack width (mm)	Average crack width per segment (mm)	Total Density (%)	Existing SDI	Proposed SDI per type of crack	Total proposed SDI	Applied proposed SDI
4+600	AC - L	0.25	5	5	0.25	10	3.41	3.41	3.41 AC
4+900	AC - L	0.48	10	10	3.31	10	5.41	10.93	10.93 AC/LC

a AC = alligator cracking, EC = edge cracking
b L = low severity, M = medium severity, H = high severity

From the results of the determination of the proposed SDI value of the nine evaluated road segments (where two road segments are shown in tables 3 and 4), it was found that generally, the proposed SDI value was higher than the existing one. Of the 141 evaluated road segments, only 28 road segments, or around 19.86%, have the proposed SDI value similar to the existing SDI (in this case, the similarity is expressed by the difference between the two by maximum values of 5 points, as shown in tables 3 and 4 parts marked with shading). The rest of the existing SDI value was under- estimate the proposed one, but there was also the existing SDI value over-estimate the proposed one, especially in a road segment that is only found one type of crack damage with low/medium severity and low density.

5. Conclusions

This paper presented a proposed surface distress index (SDI) equations to improve the effectiveness of assessing the functional condition of the road, especially for crack damage. The proposed SDI equations developed were functions of maximum SDI value for crack damage, PCI's deduct value for each density, and PCI's maximum deduct value for crack damage. It resulted in: (i) the proposed SDI equations can predict the SDI values with a difference of less than 6.2%. This shows that the proposed SDI equations can estimate SDI values quite accurately, (ii) the similarities between the proposed and existing SDI were only 19.86%. Most of the existing SDI value was under-estimate proposed one, but there was also an existing SDI value over-estimated proposed one, especially in the road segment which was only found one type of crack damage with low/medium severity and low density

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