Q-Slope and RHRS for the evaluation of highway rock slopes – Serra do Mar, Brazil

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ABSTRACT: The northern coast of São Paulo State is a region with many highways that connect the coastal cities to each other and to the State capital or other cities. These highways need to traverse the Serra do Mar mountain range. And because the State capital and other major cities are on the plateau, there is a need to overpass 700-800 meters of vertical distance in just a few kilometers of horizontal distance. Since many of the highways are around 50 years old, their design and construction had a different approach and pattern from current highway standarts. This makes the region's slopes very prone to many types of failures, like rockfalls and landslides. The highway sector studied in this paper was already studied by the some of the authors, for the application of RHRS. Here, we present an application of the Q-Slope method on the same slopes.

1 INTRODUCTION

This work presents an experimental approach of using the Q-Slope method (Barton & Bar, 2015) in a highway sector already studied (Castilho *et al.*, 2018) with the Rock Fall Hazard Rating System method (RHRS – Pierson *et al.* 1990, Budetta 2004). We do not intend to exhaust the technical aspects of the methods nor technical aspects of combining both. Rather, we seek for a fast and practical way to evaluate highway slopes that are clearly compromised and need methods to define improvement and correction planning. The authors think that the Q-Slope method fits perfectly the motto of the RHRS analysis, that is, a low cost, fast and pratical method to evaluate slopes' stability, and was a natural addition to the RHRS analysis.

1.1 *Transport corridors in the northern coast of São Paulo State*

The northern coast of São Paulo State is a region with many highways, that connect the coastal cities to each other and to the State capital or other major cities. These highways need to traverse the Serra do Mar mountain range, one of the most remarkable relief features of Brazil's southeastern coast. And because the coatal cities are close to the sea level, and the State capital and other major cities are beyond the Serra do Mar, there is a need to overpass 700-800 m of vertical distance in just a few kilometers of horizontal distance. Since many of the highways are around 50 years old, their design and construction had a different approach and pattern from current highway standarts: very sinuous alignments, high gradient ramps and vertical rock slopes with little to no stabilisation solution or support. This makes the region's rock slopes very prone to many types of failures and problems, like rockfalls and landslides.

In this context, this work presents a study carried on at a 1 km sector of the SP-055 – Rodovia Dr. Manoel Hipólito do Rêgo or Rodovia Rio-Santos highway. The SP-055 in the studied region is a single-lane two way highway.

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1.2 *The study site*

The 1 km highway stretch studied in this paper is located between the cities of São Sebastião and Caraguatatuba, and was already studied by Castilho *et al.* (2018), for the application of Rockfall Hazard Rating System. The authors of the cited work concluded that one third of the slopes in this stretch is in need of some stabilization measures, and a fifth needs imediate remediation.

The geology of the study site is composed entirely by biotite gneiss, with the foliation being the main rock discontinuity, acting alone or combined with fractures.

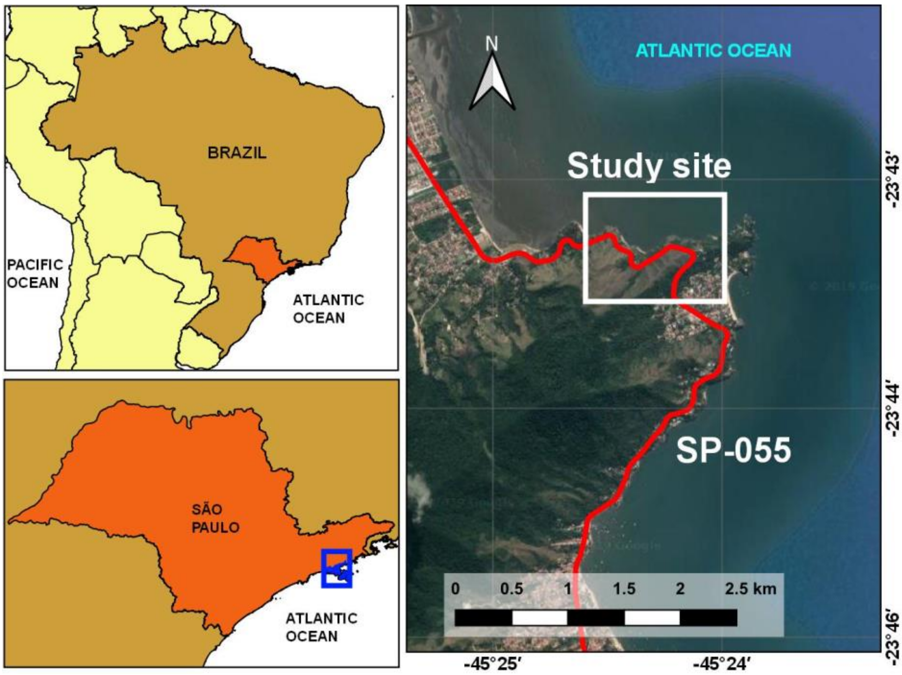

Figure 1. Study site location and the SP-055.

Figure 2. A slope just a few meters before the beginning of the studied sector. On this slope, there is already a metallic wire installed, with some rock boulders caught inside the net.

2 METHODOLOGY

The RHRS index takes into account aspects from different sources: geology of the rock mass (the slope itself), the road/highway design and construction features, climate and previous occurrences of rockfalls on a specific site. . To classify the rock slope, the RHRS needs the Slope Mass Rating (SMR, Romana 1993), and the SMR needs the Rock Quality Designation (RQD, Deere 1966).

Figure 3. A slope at the beginning of the studied site. Notice the boulders at the slope's foot, and scars of failures in the rock slope, probably from rockfall events.

Castilho *et al*. (2018) also performed kinematic analysis, and the Jr and Ja parameters from Barton *et al*. (1974) were used to estimate the friction angles.

The Q-Slope method is an empirical method to evaluate excavated rock slopes, supplementing the Q-System method with parameters adapted to slope analysis. The method was designed to be used in the field, so that an ideal slope face angle can be found, with no additional stabilisation solution. So, three parameters out of six (Jr, Ja e RQD) to apply the Q-Slope method had already been obtained when evaluating the slopes for the RHRS analysis and kinematic analysis. For this reason, and the purpose of Q-Slope, to be a low cost, fast and after excavation analysis, the application of the Q-slope method was a natural addition to the analysis.

2.1 *Field survey and data collection*

All the field data had been collected by some of the authors when conducting the studies presented in Castilho *et al*. (2018). So, it is part of the experiment to evaluate if it's possible to use the Q-slope method with already obtained data. It is also worth to notice that the authors have familiarity with the Serra do Mar region and the study site, because of years of working around the region for highway projects.

Some re-evaluations for SMR and RHRS calculations were made, using the base values from Castilho *et al*., but the overall results did not change.

2.2 *Past rockfall and slope failures occurrences*

Castilho *et al*. (2018) presents registers of many occurrences of rockfalls and slope failures in the studied highway sector or in areas nearby. Although that work was published in September of 2018, many more occurrences have been registered by the local press after heavy rainfall events.

At October 12th, 2018, the Tamoios highway (SP-99) was blocked for 30 hours, because of landslides.

At November 7th, 2018, the same highway was blocked again, for 80 hours, with registers of landslides and falling trees.

In February 2019, the Tamoios highway have been blocked 3 times, for periods of some hours, because of havy rainfall, triggering the alert for landslides.

At February 6th, 2019, landslides and rockfalls have ben registered at the SP-55 highway in a location very close to the study site. The rainfall amount for 72 hours was 167 mm.

Figure 4. Recent (February, 2019) landslides and rockfalls registered by the local press close to the study site at the SP-55 highway.

All these examples illustrate that the use of assessment tools and methods like RHRS, SMR and Q-slope are urgent, and every heavy rainfall event causes recurrent mass movements.

3 RESULTS

The results of the Q-Slope analysis are presented in the figure below, together with results of SMR and RHRS from Castilho *et al.* (2018). The next figure, shows the Q-slope results plotted in the Q-slope stability chart.

SLOPE	RHRS	SMR	Q-Slope		
			Q	Current Angle	β
TA-1	243	67	0,27	90	54
TA-2	297	85	0,59	85	60
TA-3	278	85	0,59	80	60
TA-4	333	68	0,44	80	58
TB-1	303	71	0,03	80	35
TB-2	466	73	0,05	60	39
TB-3	465	39	0,03	80	33
TC	551	19	0,03	80	33
TD	258	39	0,06	50	40
TE	230	51	0,01	70	26
TF-1	249	56	0,13	75	47
TF-2	252	70	0,19	72	50
TG	253	55	0,02	85	32
TH	144	66	0,03	80	34
TI	487	48	0,01	85	28

Figure 5. Results of Q-slope, RHRS and SMR.

All of the 15 analyzed slopes fall in the “Unstable” area of the Q-slope chart. From Figure 5, one can notice the difference between some slopes with low (good) RHRS score but bad Q-slope index. The first point to consider is that each method measures different things: RHRS purpose is to measure risk exposition of users along a highway. This means that an unstable slope may present no risk if there is space for rock boulders to stop before reaching the highway. Q-slope purpose is to measure how stable or unstable a slope is.

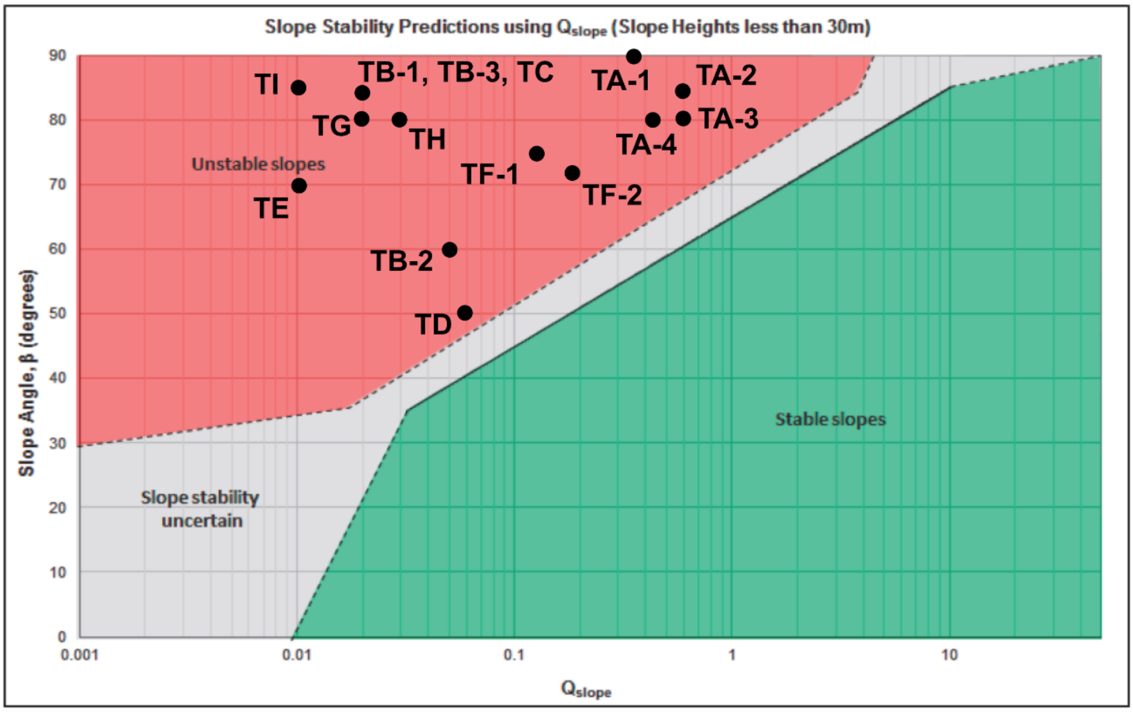

Figure 6. Results of Q-slope.

With this distinction in mind, it is still useful to investigate the reason for the differences. The main factors identified by the authors are:

Height and slope angle: many of the slopes are below 7,5 or 15 meter high. So their score for RHRS is low. It maybe argued too that RHRS doesn't take into account the slope face angle, and this is a major factor in determining stable or unstable slopes for Q-slope. So, TA-1 for example is a 6 m high, 90º slope. It is in the lowest (good) score zone for RHRS in the Height factor, but it is the worst possible for Q-slope because of it's angle. The slope angle for RHRS is inside the SMR analysis. But SMR uses the slope angle when determining weights, not in the final classification like Q-slope. Also, SMR is one factor among 9 others when calculating RHRS. In other words SMR is 11,11% of RHRS final score, so even if the slope angle is critical, its effect is diluted in the RHRS index.

The angle influence in SMR and RHRS is clear in the parametric study presented in Figure 7. SMR and RHRS were calculated for 3 slope angles (30°, 45° and 60°) plus the actual angle for 3 slopes. The SMR values changes, but the RHRS does not. The Q-slope numeric value does not change, but the condition (stable or unstable) does change, this is illustrated by the colors background in the table. The reason why these changes in SMR do not affect RHRS is the way RHRS calculates weights: by using exponential functions. In Figure 8, it is possible to see that from SMR values 40 to 100, there is a difference of just 10 points in 81 possible for the SMR weight. So, a 60% variation on SMR values (the higher ones), only results in 1,4% variation on RHRS final score.

Climate conditions (rainfall amount): the highest score for RHRS is with a rainfall amount of 1.200 mm. The studied region has a annual mean rainfall amount of 2.500 mm. More than double the highest score. Events of 100 or 150 mm in a day are not rare during summer. Maybe more score bands or more weight could be added to RHRS to better reflect tropical conditions with severe storm events. If a value of 2.500 is used in the formula, a result of 9.000 is obtained, which is clearly not intended by the method authors. It can also be argued that tropical climate causes a more intense weathering, which could affect SMR values too. Maybe an adapted RHRS method to tropical conditions could yield very different results

SLOPE	TA-1			
ANGLE/INDEX	30°	45°	60°	90° (original)
SMR	91	72	68	67
RHRS	243	243	243	243
Q-Slope	0,26	0,26	0,26	0,26
SLOPE	TB-3			
ANGLE/INDEX	30°	45°	60°	80° (original)
SMR	76	76	76	39
RHRS	459	456	459	465
Q-Slope	0,025	0,025	0,025	0,025
SLOPE	TI			
ANGLE/INDEX	30°	45°	60°	85° (original)
SMR	68	51	48	48
RHRS	484	486	487	487
Q-Slope	0,013	0,013	0,013	0,013

Figure 7. Parametric study with varying slope angles. Results of Q-slope, RHRS and SMR.

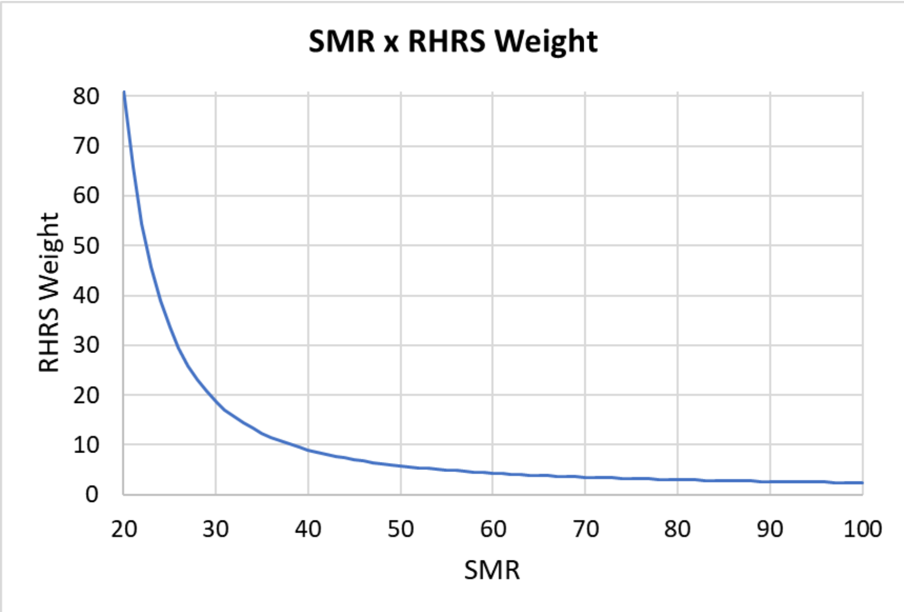

Figure 8. Variation of SMR weight in RHRS final score.

Frequency of rockfall: since there is no official data base for rockfall, landslides and mass movements records, the values used (3 events per year) may be underestimated. The absence of these records affects the Average Vehicle Risk and the Block Diameter too.

Percent of decision sight distance: many of the slopes have a high score for this value, usually being above 100%, placing them in the lowest score band.

With these factors in mind it is important to remember that RHRS is engineered towards highway analysis, and may compensates some geological conditions with actual road conditions, if the road has features to minimize damage by rockfall events. In the SP-55 sector studied here, some of the slopes do have these conditions, like Percent of decision sight distance.

The map of Figure 7 is a systhesis map of the integrated RHRS and Q-Slope analysis, and follows the same pattern adopted by Castilho *et al.* (2018). Easy to recognize patterns were used so that even a non-technical (in terms of geology and geotechnics) person, like a government or highway authority can understand the results of the study. With this map, and the “Beta” angle from Q-slope, a highway authority can easily foresee the first approach to slope improvement, that is, re-sloping

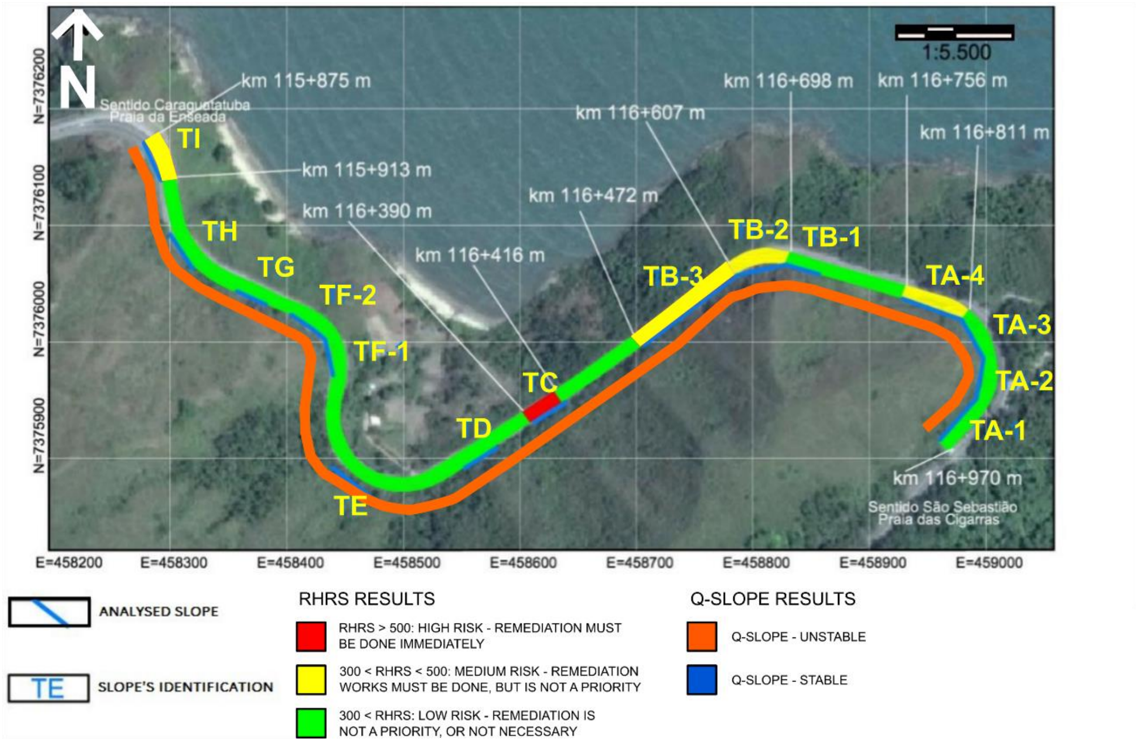

Figure 9. Synthesis map of the integrated RHRS and Q-slope analysis.

3.1 *Relationship between Q-Slope and SMR*

Since RHRS relies its geological portion on SMR, it's natural that one looks for a relationship between Q-slope and SMR. Jorda-Bordehore *et al.* (2018) have in fact made this study, analyzing 57 cases from Bolivia, Ecuador, Laos, Peru and Spain, and more than 10 rock types. Those authors have come to a preliminary relationship, expressed by the equation below:

$$SMR_{line-of-best-fit} = 7.4219(Q_{slope}) + 47.196$$

Here, we present the data from this study plotted against Jorda-Bordehore's equation. The data from this work is not enough (in terms of amount, geological settings and locations) to confront the data from Jorda-Bordehore *et al*. It is just a comparison to see how our data fits into a larger in broader dataset.

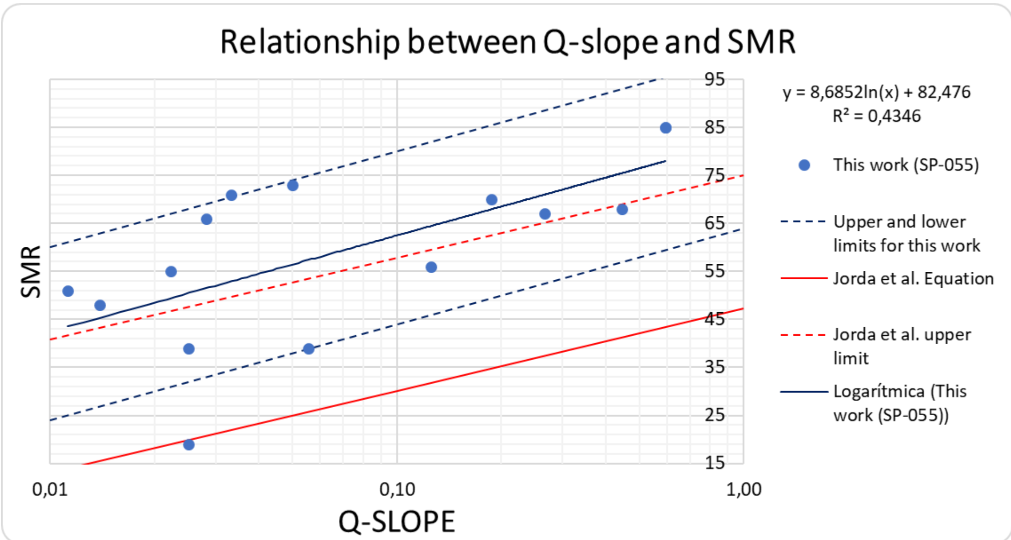

Figure 10. Relationship between Q-slope and SMR, using Jorda-Bordehore *et al.* (2018) equation.

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4 CONCLUSIONS

The studied slopes have a face angle around 70-90º in general and the calculated Q-Slope value was always below 0,5. So, all of the slopes are inside the "Unstable Slopes" area in the Q-slope stability chart. This is consistent with the fact that in many cases, the rock foliation is unfavorable to the cut, fallen rock blocks are visible along the stretch in many sites and there are occurrences of rockfalls reported.

On the other hand, 9 out of 15 slopes had a RHRS index below 300, meaning they have low risk and low priority of action or need no action. This fact probably is due to non-geological factors having an important role in RHRS final index, like percent of distance view sight. Differences in how each method sees related factors are also of importance, like slope height and angle. Also, the importance of SMR inside RHRS is only around 10%, and higher SMR values do not change RHRS final score.

To sum up the results of the work presented here, parameters from a previous work were used to achieve a Q-Slope value and an ideal slope angle ("Beta") for rock slopes already analyzed with RHRS indexes. With RHRS, the highway authorities can decide where to act first, and with Q-Slope, they can have a first approach to what would be (and how much it would cost) a simple re-sloping solution. Although re-sloping may not be feasible in many cases, Q-slope provides a first basis from where other stabilization solutions (like soil nailing or retaining walls) can be compared, considering costs and execution aspects.

The authors would like to emphasize the need of more studies and research using empirical methods like RHRS and Q-slope in different lithologies (for example sandstones and basalts) and geological contexts around the country. Rocks in general have distinct behavior against Brazil's climates, when compared to northern hemisphere climate (for example in USA states, where RHRS was developed). This presents a major challenge for the Brazilian geological and geotechnical community: to deal with risks in highway slopes with varying lithologies and with the need for tools adapted to tropical conditions.

A RHRS method adapted and calibrated to tropical conditions, with more weight or score bands to climate, and more weight to SMR, is needed. Q-slope is already adapted to tropical conditions and yields consistent results. The combination of both, presented here, is already useful. A combination of Q-slope with an adapted RHRS will be even more.

Another emphasis the authors would like to make is a reservation for the use of empirical methods like Q-slope and RHRS: these methods are meant to be used in practical, construction site or operating highway conditions. For design phase, the usual design methods and tools, more time and resource consuming, are needed and essential.

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