IDENTIFICATION OF HYDROPLANING RISK AREAS IN EXPRESSWAYS: A CASE STUDY ON SOUTHERN EXPRESSWAY, SRI LANKA

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ABSTRACT

Safety is one of the main functional requirements of expressways which are designed to operate at 100km/h. One of the key considerations in providing safety is ensuring adequate frictional performance especially during wet weather. Hydroplaning is a phenomenon that occurs on wet pavements which poses a serious safety risk to vehicles especially on high speed roadways. Vehicles subjected to hydroplaning are likely to be involved in fatal or grievous accidents. There are several roadways, vehicular and environmental causal factors that contribute to the hydroplaning. A speed at which a vehicle hydroplaning is dependent on its tire pressure, wheel load, tire thread pattern, pavement micro texture and the water film depth generated during the rainfall among several other parameters. For expressways where vehicles generally travel at high speeds controlling development of Water Film Thickness is particularly important. The road alignment and longitudinal cross sectional profile play an important role in affecting water film thickness generated during the rainfall event. Depending on the water film thickness generated on road segment, the hydroplaning risk for a given operational speed, vehicle characteristic will vary. This methodology is applied on the Southern Expressway-Sri Lanka to identify road segments that have higher hydroplaning risk.

Several locations were observed as water stagnating areas and one of them was used in the study. Gallaway formula and Road Research laboratory (RRL) method were used to find the estimated water film thickness and the contour maps of flow depths for different rainfall intensities were developed for the road segment. Based on the water film thickness, contour maps and the hydroplaning speed derived for the water film thickness and hydroplaning risk prone areas were identified.

This will be useful for further study of these areas and to propose possible design or repair mechanisms. Further such a study will be helpful for the design of new expressways covering the whole island in the future.

ACKNOWLEDGEMENT

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I first wish to thank the Transport Engineering Division of Department of Civil Engineering, Faculty of Engineering, University of Moratuwa for selecting me to follow this master's course of highway and traffic engineering.

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My heartfelt gratitude goes to Dr.H.R.Pasindu for his kind guidance, valuable comments and continuous support throughout this research. The knowledge I had from him apart this research work but in the lecture room level was also invaluable and greatly helped me to be shaped into an academically sound Engineer in my work place.

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LIST OFABBREVIATIONS

Abbreviation	**Description**
RRL	Road Research Laboratory
NASSRA	National Association of Australian State Road Authorities
AASHTO	American Association of State and Highway Transportation Officials
WFD	Water Film Depth
WFT	Water Film Thickness
RDA	Road Development Authority
VMS	Variable Message Sign
ER	Exceedance Ratio
MTD	Mean Texture Depth

CHAPTER 1

1 INTRODUCTION

1.1 General Background

Expressway network is a resent revolution of Sri Lankan saga of highway engineering. A major problem in designing the expressways was lack of design standards suitable to Sri Lankan conditions. This has paved way to some of the flaws that are detrimental for the traffic safety of the expressways. Hydroplaning or Aquaplaning is one such problem where attention is needed at this functional stage.

In the case of wet pavement, the contact between the vehicle's tyres and the road pavement is lost in the presence of film of water.This separation may be fully or partially. This results in the loss of normal friction between the tyres and the road surface and hence the vehicle control is lost which can lead to serious accidents. This may be illustrated as shown Figure 1-1.

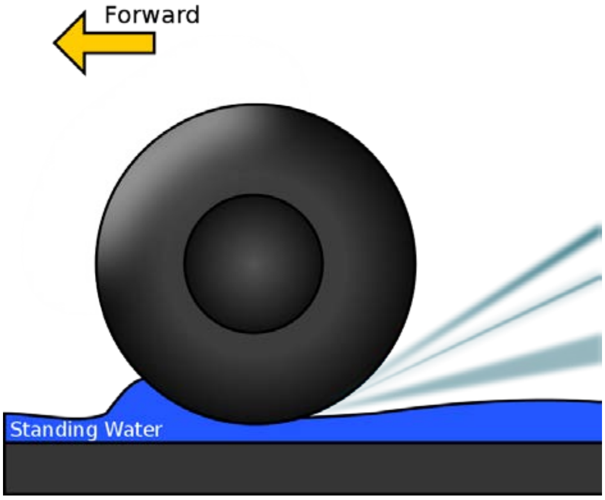


Figure 1-1Loss of contact between the road surface and the tyre(ZitaLangenbach, 2015)

The hydroplaning risk is increased with the accumulated water film thickness. In the event of a rain, the hydroplaning risk is increased especially in a road of flat terrain. This phenomenon is going to be worst in the transition of superelevated curves where the locations having very less pavement cross slope. The drainage rate is very slow in these nearly flat areasand the water film thicknesses are high. The separation of tire and the pavement is illustrated in Figure 1-2

Figure 1-2 Separation between the road surface and vehicle tire (Foucard-2005)

1.2 Objectives

The objectives of the case study are to calculate the water film thicknesses of a location in the superelevation transition region of a horizontal curve in southern Expressway and hence identification of risk prone area of the road segment.

1.3 Problem Statement

It is observed that the accident rate of expressways in Sri Lanka is higher in the location with horizontal curve having superelevation transition in the case of rain. This is mainly due to accumulation of water in the vicinity of nearly zero pavement cross slope. It is important to identify the regions of risk prone areas with respect to the level of the severity.

1.4 Scope of the report

This report is aimed at presenting the degree of hydroplaning risk of a selected location in southern expressway for different rainfall intensities for the existing condition. Then it presents the risk prone areas for 0.5% gradient and different rainfall intensities. (0.5% is the minimum vertical gradient provided for drainage purpose in superelevation transition region)

CHAPTER 2

2 LITERATURE REVIEW

2.1 Hydroplaning Effect

Hydroplaning or Aquaplaning is a phenomenon that happens in the presence of water between the road surface and the vehicle tyre. The friction between the two surfaces is reduced and ultimately the tyres are subjected to slides. This phenomenon is called hydroplane. This is shown in Figure 2-1.

Figure 2-1Hydroplaning at curved section

2.2 Types of Hydroplaning

There are two types of hydroplaning. (John Chesterton et. al, -2006) demonstrate these types as follows.

Viscous Hydroplaning

This type of hydroplaning is occurs due to presence of very thin water film. In this case, the vehicle slides due to reduction of friction between the tyre and the surface.

Dynamic Hydroplaning

Dynamic hydroplaning occurs due to formation of water layer on the road surface. When a vehicle travels through this water layer if forms a water wedge under the tyre. The time available to escape this water wedge is reduced with the speed of the vehicle. This leeds to highly pressurize the water wedge under the tyre. Increase of this water pressure leads to uplift the vehicle when the force is equal to the weight of the vehicle.

Benjamin Dudman-2014 discussed about three types of hydroplaning as Viscous, Dynamic and tyre tread rubber reversion hydroplaning.

This case study is based on the Dynamic Hydroplaning.

2.3 Factors Affecting to Dynamic Hydroplaning

There are several factors affecting to the dynamic hydroplaning. (John Chesterton et. al, -2006 discusses the factors as follows)

2.3.1 Environment

The most important environmental factor in hydroplaning israinfall intensity.

2.3.2 Road Geometry and Pavement Material

This has the large effect of water depth. When the flow paths are longer the water take more time to exit from the road surface and it leads to accumulate more water in higher depths on the road. Transition in superelevation, and sag curves are some of risk prone areas where the slope is low. Superelevation changes can results in long curving flow paths where leading to higher risk.

2.3.3 Pavement Drainage

Pavement drainage devises such as roadside channels, kerbs, grated inlets should be introduced where necessary. Maintaining these systems is very important to minimize the hydroplaning risk.

2.3.4 Vehicle characteristics and Behavior

Vehicle characteristics and behavior are very significant factors in hydroplaning. This includes the weight of the vehicle and tyre characteristics. Higher the weight of vehicle, the uplift force to hydroplane is higher. Hence the lighter vehicles will hydroplane in lower speeds. Deeper tyre thread depths remove the water away from contact area more effectively. Worn tyres increase the severity of the hydroplaning.

Austroads (Guide to Road Design Part 5A: Drainage) shows the followings as governing factors of hydroplaning.

- Road Geometry
- Road surface texture, porosity and rutting
- Operating speed
- Rainfall intensity
- Water film depth
- Tyre thread depth, vertical load, width of tyres and tyre pressure
- Driver behavior

2.4 Hydroplaning Speed

Hydroplaning speed is the vehicle speed at which the hydroplaning occurs.(Benjamin Dudman-2014) says there is low potential to happen full hydroplaning at lesser speeds. but the partial hydroplaning can be occurred at lower speeds. Full hydroplaning is drastically increased with the speeds greater than 80mk/h.

(Ghim Ping ONG et, al, 2007) defines the Hydroplaning speed as “the speed at which the tyre is compete separated from the pavement surface by a film of water, or the fluid uplift force developed beneath the tyre is equal to the wheel load. (Horne and Dreher, 1963).This a measure of the hydroplaning potential of a wet pavement with a known water film thickness. When the hydroplaning speed is higher, the hydroplaning potential is lower. (Ghim Ping ONG et, al, 2007)

2.5 Assessment of Hydroplaning parameters

There are various equations and models developed for calculation of hydroplaning parameters and they can be divided into two types as

1. Empirical equations
2. Analytical equations

2.5.1 Gallaway Equation

This empirical equation is developed by Gallaway B.M. et al in 1971) to determine the water film thickness of the pavement (WFT).

$$D = \frac{0.103 \times T^{0.11} \times L^{0.43} \times I^{0.59}}{S^{0.42}} - T \qquad \text{..................(2.1)}$$

Where, D - WFT above the pavement (mm)

T – Average pavement texture depth (mm)

L –Drainage path Length (m)

I – Intensity of Rainfall (mm/h)

S – Slope of drainage path Slope (%)

Average pavement texture depth of 0.4mm is considered as desirable minimum by Benjamin dudman-2014 for the higher speeds greater than 80km/h and 0.2mm for design speed lesser than 80km/h.(John Chesterton et. al, -2006) recommended the 0.5mm pavement texture depth.

2.5.2 Road Research Laboratory (RRL) Equation

This empirical method is based on the NASSRA ‘Report of Investigation into the drainage of Wide Flat Pavement’ (1974) and the RRL ministry of Transport Report No.LR236 (1968).

$$d = 0.046 \frac{(L_f I)^{\frac{1}{2}}}{S_f^{\frac{1}{5}}} \qquad \text{……………….(2.2)}$$

Where d = Depth of flow or water film thickness (mm) at the end of the flow path
L_f = Length of flow path (m)
I = Rainfall intensity (mm/hr)
S_f = Flow path slope

$$S_f = (S_l^{\,2} + S_c^{\,2})^{\frac{1}{2}} \qquad \text{……………….(2.3)}$$

Where S_l = Longitudinal slope (grade)
S_c = Cross fall of pavement

$$L_f = W \frac{S_f}{S_c} \qquad \text{……………….(2.4)}$$

Where W = Width of the pavement contributing to the flow

RRL method doesn’t consider on pavement texture depth.

2.5.3 Ivey, et al (1975)

A behavioral effect of driver sight distance is calculated with this empirical equation developed by Ivey, et al (1975). This gives the relationship between the rainfall intensity and the visibility.

$$S_v = \frac{2000}{i^{0.68}} \frac{40}{V_i}$$ ……………….(2.5)

Where S_v = Sight distance (ft)
i = Rainfall intensity, in/hr
V_i = Vehicle velocity, m/hr

2.5.4 Horne (1962)

Horn derived an analytical equation to indicate the relationship between the tyre pressure and hydroplaning speed in1962.

$$V_p = K\sqrt{p}$$ ……………….(2.6)

Where V_p = Tyre aquaplaning speed (mph)
K = Constant dependant on fluid and flow dynamics determined from experimental data for specific tyre and road combinations
P = Tyre inflation pressure (psi)

It is found by Horne et al (1962) that the constant K = 10.35 which is shown with the experimental data obtained from aircraft aquaplaning data.

2.5.5 PAVDRN, NCHRB Web Report 16 (1998)

The University of Pennsyivania developed this analytical equation in 1998 by a computer program called PAVDRN. This equation derived for fixed tyre condition of 2.38mm tread depth and 167.5 kPa of tyre pressure.

$$WFD = \left[\frac{nLI}{105.425S^{0.5}}\right]^{0.6} - MTD$$ ……………….(2.7)

Where WFD = Water Film Depth (mm)
MTD = Mean Texture Depth
S = Slope (m/m)
I = (i – f) = Excess rainfall rate (mm/hr)
i = Rainfall intensity (mm/hr)
f = Infiltration rate or permeability of pavement (mm/hr)
n = Manning’s roughness coefficient

$$n = \frac{1.49S^{0.306}}{N_R^{0.424}} \quad \textit{(Porous asphalt)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2.8)$$

$$N_R = q/\nu \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2.9)$$

Where N_R = Reynold's number
q = Quantity of flow per unit width ($m^3/s/m$)
ν = Kinematic viscosity of water

This equation accounts for speed reduction due to lower visibility derived by Ivey et al (1975)

2.6 Simulation Model for Hydroplaning

This is a three dimensional simulation modal introduced by Ghim Ping ONG et, al, 2007 to analyze the hydroplaning effect. It is consist of three components as

1. Tyre modal

2. Fluid model

3. Pavement surface model

These components and there input parameters are shown in the following diagram.

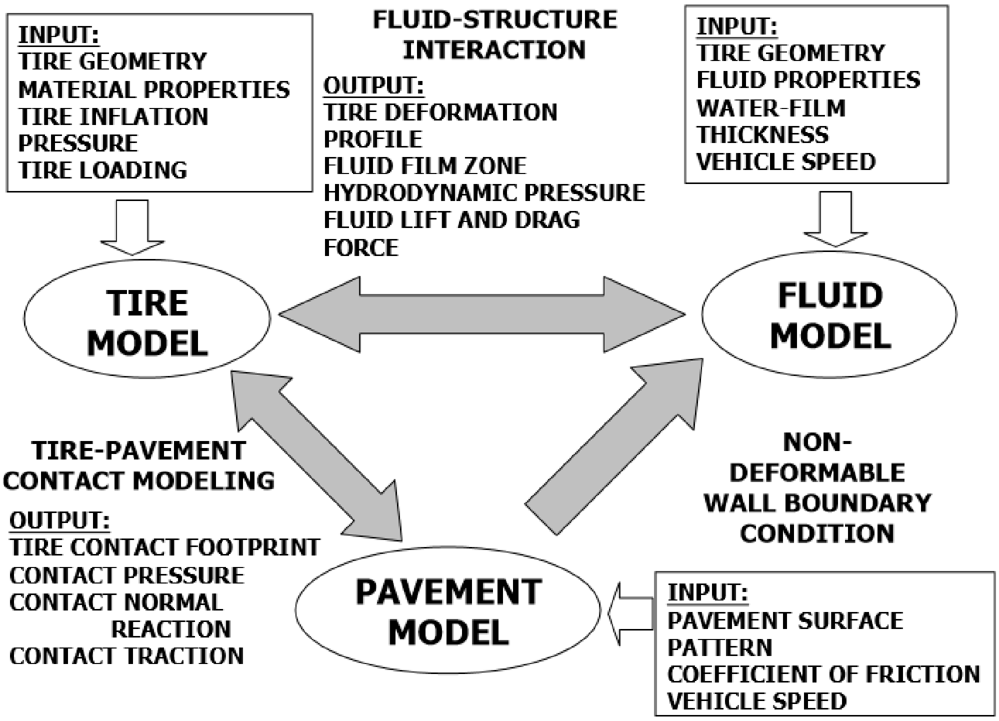


Figure 2-2Components of hydroplaning simulation model

The illustration of main three dimensional finite element simulation models are shown in figure 2-3 and 2-4.

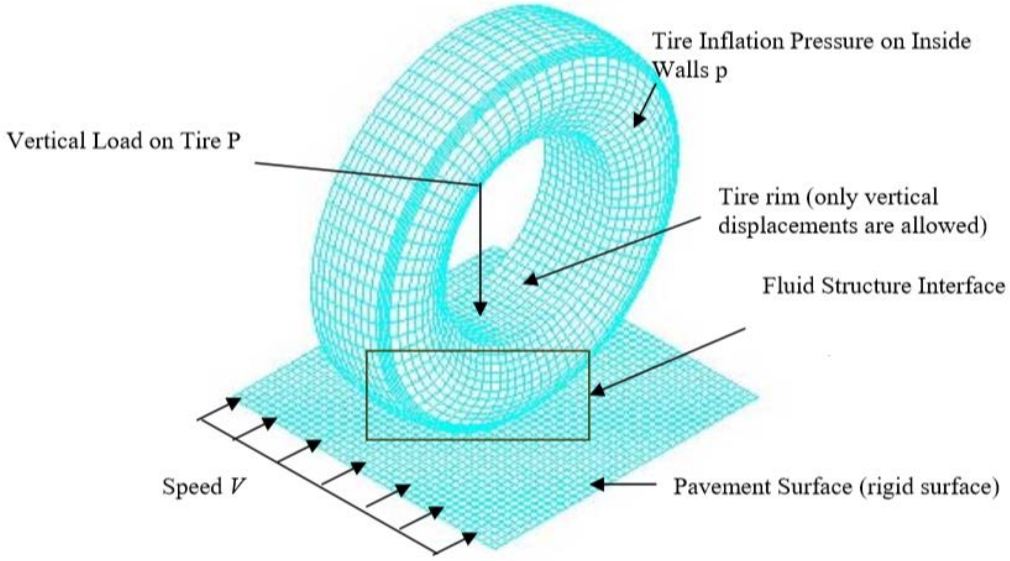


Figure 2-3Pneumatic tyre model

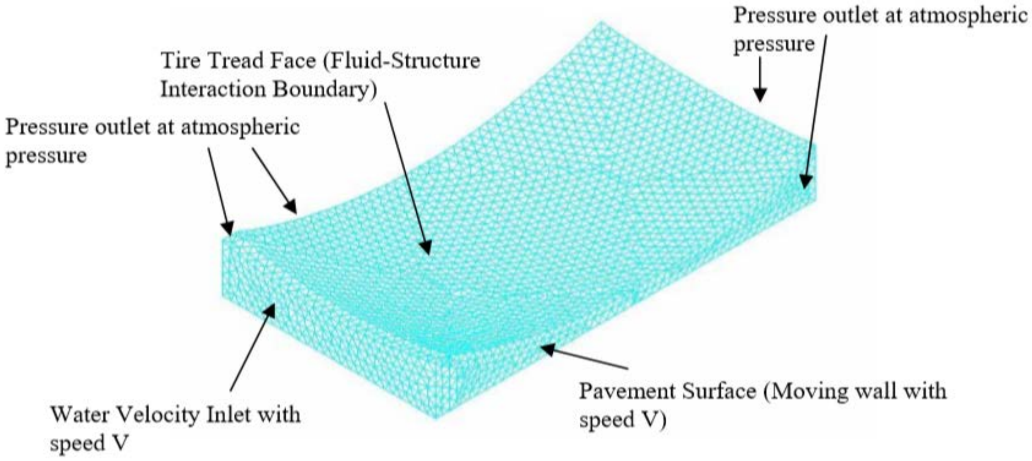


Figure 2-4Fluid model (beneath the tyre)

To simulate the phenomenon, the finite element software package of ADINA is used and for the analysis of both tyre and fluid model, mesh convergence analysis method is used.

By this computer simulation analysis modal, the followings are determined by (Ghim Ping ONG et, al, 2007).

- Hydroplaning speed
- Effect of tyre pressure on hydroplaning
- Effect of footprint aspect ratio on hydroplaning
- Effect of water film depth of hydroplaning
- Comparison of factors affecting hydroplaning
- Relationship between the hydroplaning speed and various parameters

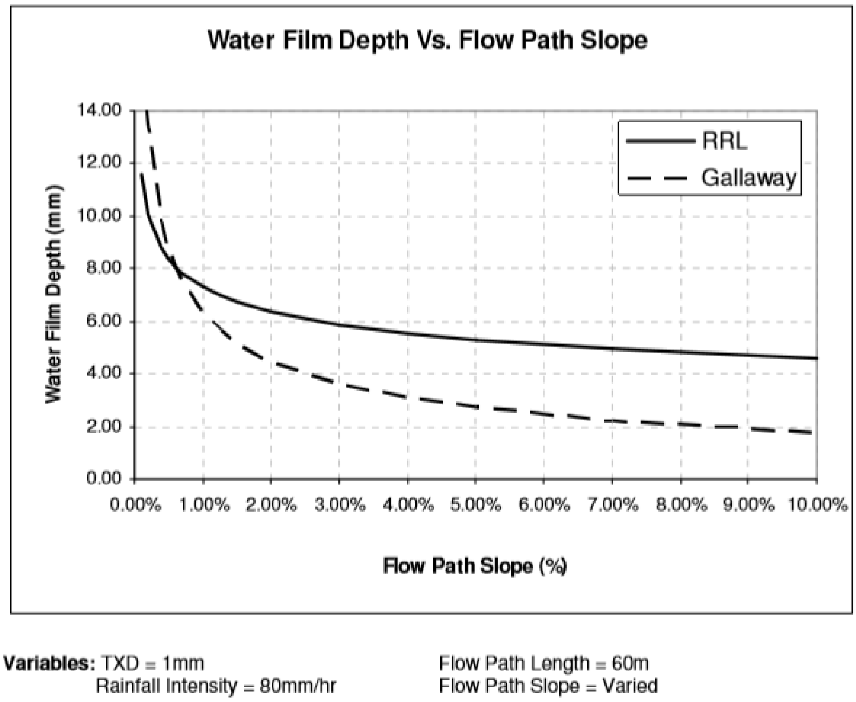
2.7 Comparison of Gallaway and RRL Formula

This case study is mainly based on the Gallaway and RRL formulae. Hence it is important to compare the results derived from the two equations.

John Chesterton et al (2006) compares the WFT calculated by the two equations with respect to following variables.

- Slope of the flow path
- Length of the flow path
- Surface Texture Depth
- Rainfall Intensity

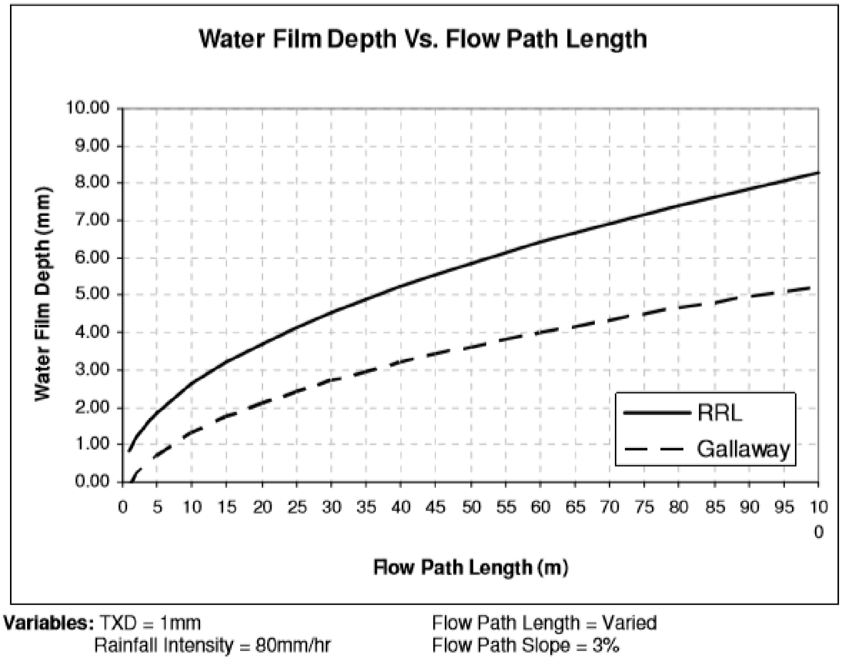
2.7.1 WFD vs Flow path slope



Variables: TXD = 1mm
Rainfall Intensity = 80mm/hr
Flow Path Length = 60m
Flow Path Slope = Varied

Figure 2-5 WFDvs Flow path slope

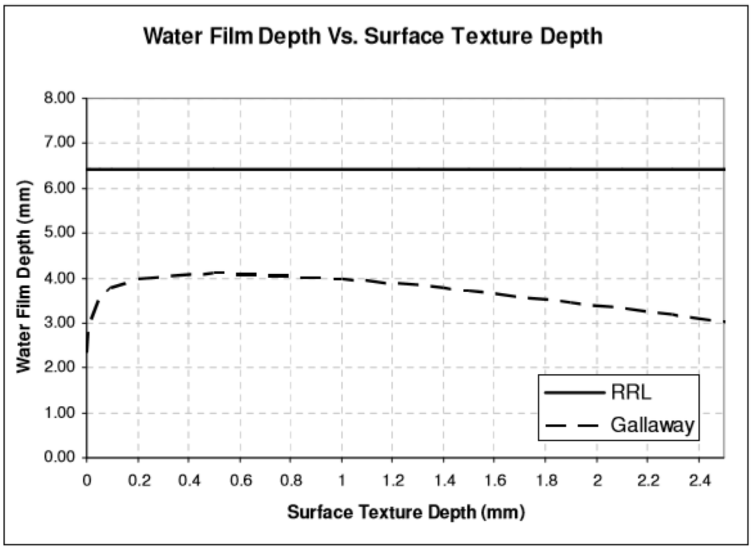
2.7.2 WFDvs Flow path length



Variables: TXD = 1mm
Rainfall Intensity = 80mm/hr
Flow Path Length = Varied
Flow Path Slope = 3%

Figure 2-6 WFDvs Flow path length

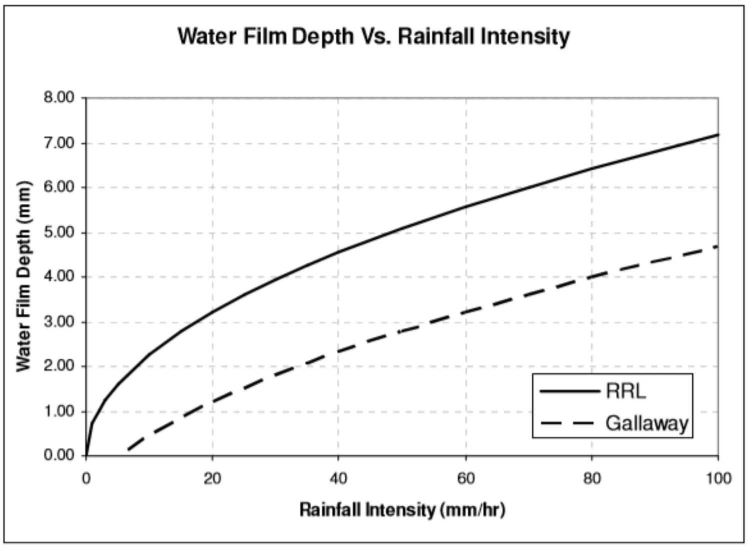
2.7.3 WFD vsTexture Depth



Variables: TXD = Varied Flow Path Length = 60m
Rainfall Intensity = 80mm/hr Flow Path Slope = 3%

Figure 2-7 WFDvs Texture Depth

2.7.4 WFDvsRainfall Intensity



Variables: TXD = 1mm Flow Path Length = 60m
Rainfall Intensity = Varied Flow Path Slope = 3%

Figure 2-8 WFDvs Rainfall Intensity

2.8 Techniques for Reducing Hydroplaning Potential

Benjamin Dudman (2014) identified the methods to reduce the hydroplaning potential and discussed those under five categories as follows.

1. Short term preventive actions
2. Design considerations
3. Geometric solutions
4. Surfacing solutions
5. Drainage solutions

2.8.1 Short Term Preventive Action

These are the methods that can be introduced within a short time and cost effective. Hence these types of methods are very important to lower the risk to the travelling public quickly until a permanent solution is adopted.

2.8.1.1 Signage

Signage is a simple method that can be effectively notifying the road users of possible risk of hydroplaning. Dudman recommended two types of signage as permanent signage and Variable Message Sign (VMS).

Figure 2-9 Permanent signage

2.8.1.2 Lateral Groves

Effective texture depth can be increased by cutting grooves in the hydroplaning hazardous area. Grooves may be cut longitudinally or in transverse direction.

Grooves increase surface water flow rate from the pavement surface to the road edge. Dudman recommends this method for concrete and asphaltic surfaces and grooving is not recommended for porous asphaltic and open graded asphaltic friction surfaces.

The following equation is developed to calculate the grooved macrotexture (ICAO,2012)

$$M_g = \frac{WD + M_u (S-W)}{S} \qquad \text{……………….(2.10)}$$

Where: M_g - GroovedMacrotexture

W- Groove Width

D - Groove Depth

M_u- Ungroovedmacrotexture

S – Groove Spacing

2.8.2 Design Considerations

In this case hydroplaning risk is address in the design stage of the road. It should be identified the hydroplaning risk area of the road in the design before construction. Following design principles could be adopted to minimize the hydroplaning potential.(Dudman ,2014)

1. Maximizing longitudinal grade in the flat terrain.
2. Increasing cross slope
3. Maximizing superelevation rotation rate
4. Co-ordinating horizontal and vertical geometry
5. Increasing road texture depth

2.8.3 Geometric Solutions

Water film thickness is reduced by reducing length of flow path and increasing the slope of flow path.

Introducing diagonal crown and Staggered Roll-over are the geometric solutions for mitigation of hydroplaning risk.

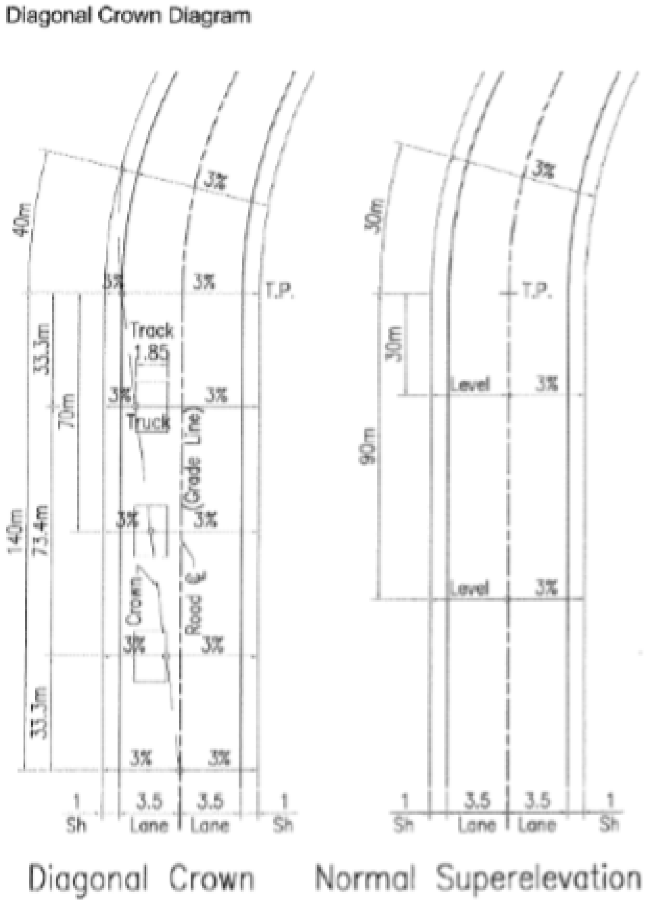
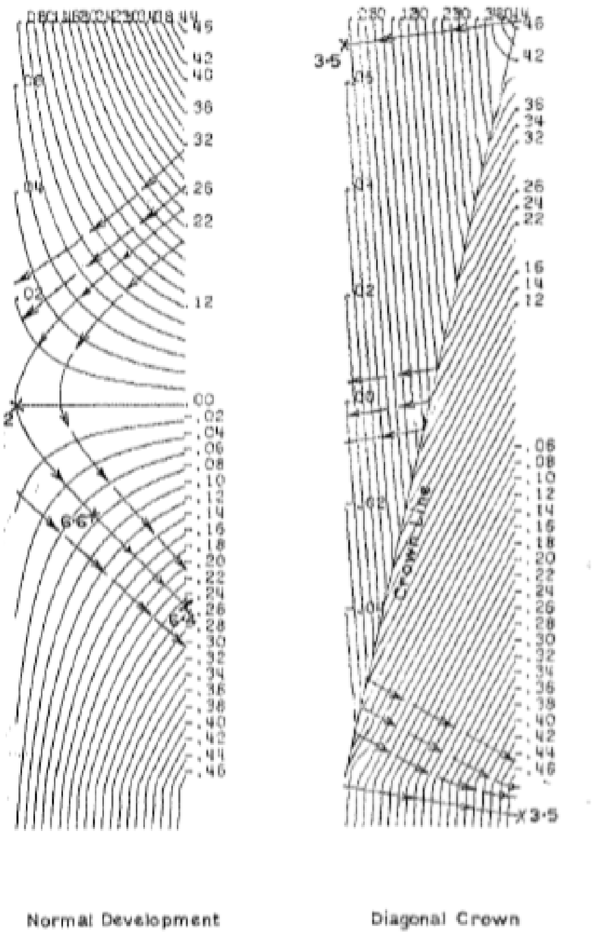


Figure 2-10Diagonal Crown (Spillane, 2003)

The reduction in length of flow path can be shown in the figure 2-11.



Normal Development Diagonal Crown

Figure 2-11 Normal flow paths and Diagonal Crown Flow Paths (Oakden, 1977)

2.8.4 Surfacing Solutions

It is possible to reduce the water film thickness by increasing texture depth or increasing permeability of surface material. For this purpose porous asphalt or pervious concrete can be used.

2.8.5 Drainage Solutions

Adequate Road edge drainage and grated trench drains can be introduced to minimize the potential of hydroplaning.

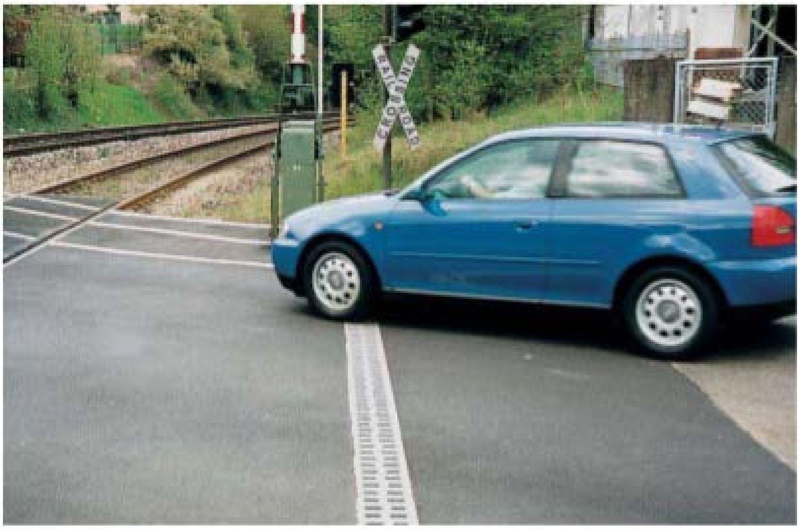


Figure 2-12Grated trench drains

CHAPTER 3

3 EVALUATION PROCEDURE

3.1 Methodology (For Reverse curve)

There are several locations identified in Southern Expressway where the accident rate is high in the case of rainy weather condition. Section of Chainage 20+660 to 20+880 is a superelevation transition region of two reverse curves having radius of 2100m. The vertical gradient of this road stretch is 0.24% which is lesser than the minimum gradient provided for superelevation transition sections (0.5% of minimum gradient of 0.5% is provided within superelevation development length).

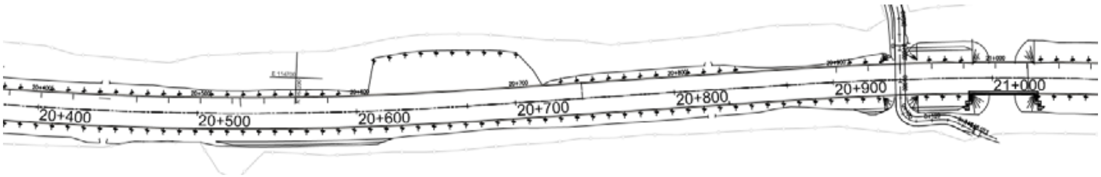


Figure 3-1Plan view of the study location

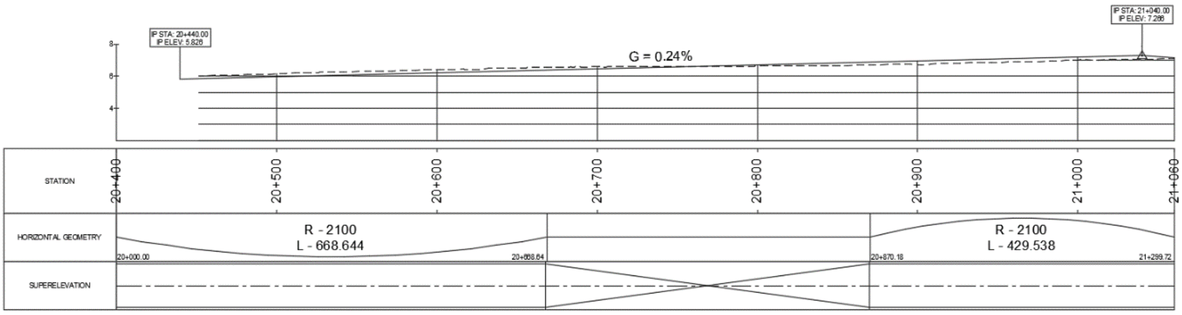


Figure 3-2Longitudinal Profile of the study location

For this location, the water film thickness is calculated along the drain paths by using the Gallaway equation for 0.5% vertical gradient and for the different rainfall intensities.

Then the contour plan of the water film thickness is plotted. For this purpose, CIVIL 3D design software is used.

For the same rainfall intensities, the WFT is again calculated with RRL method and developed the relevant contour plans to compare the results obtained from Gallaway method.

Based on the hydroplaning speed applicable for the different water film thicknesses, the exceedence ratio is calculated.

$$\text{Exceedance ratio} = \frac{\text{Operational Speed}}{\text{Hydroplaning Speed}}$$

According to the exceedence ratio, the risk contour maps showing the severity level of the selected location are generated.

This procedure is continued for the existing road condition of the selected road section.

3.2 Calculation of WFD using Gallaway Formula

This Equation is developed by Gallaway et al in 1979 to calculate the Water film depth, D

$$D = \frac{0.103 \times T^{0.11} \times L^{0.43} \times I^{0.59}}{S^{0.42}} - T \qquad \text{……………….(3.1)}$$

- Where,
  - D = Water film depth above the top of pavement texture (mm)
  - T = Average pavement texture depth (mm)
  - L = Length of drainage path (m)
  - I = Rainfall intensity (mm/hour)
  - S = Slope of drainage path (%)

3.2.1 Finding the Variables of the equation

Step 1 Average Pavement texture depth (T)

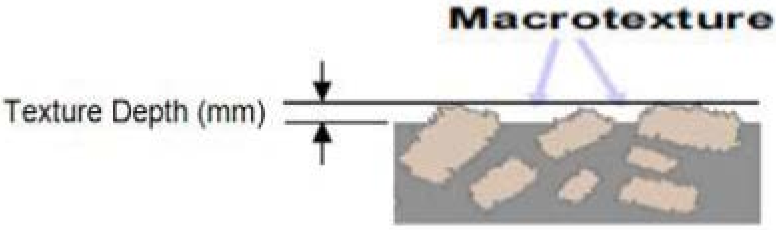


Figure 3-3Illustration of Macro Texture

The observed average texture depth is **0.4mm.**

Step 2 Calculation of Drainage path Length, (L)

Contour map of the road surface is developed and the several drainage paths are plotted to cover the problematic area based on the contour lines. The following diagram shows the drainage paths drawn for the study area.

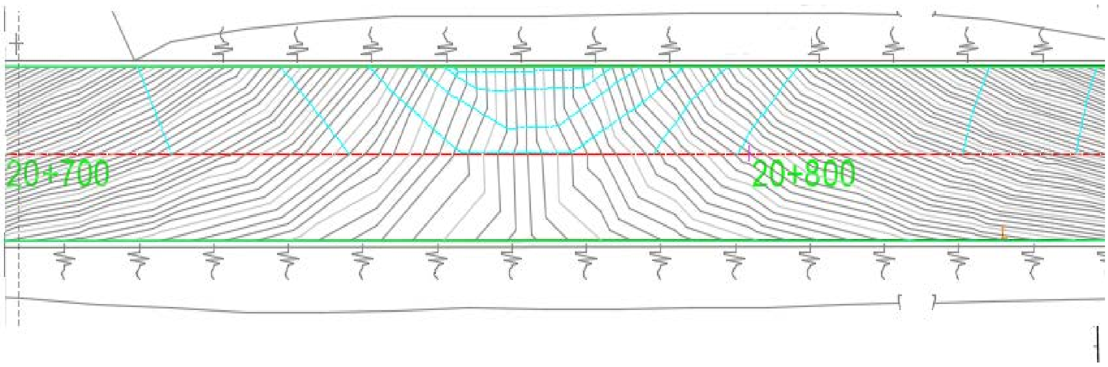


Figure 3-4Drainage flow paths

The drainage path length is the length from the starting point of water flow path to the point of analysis.

Step 3 Estimation of slope of the drainage path (S)

Corresponding to each drainage flow path, the elevations of each point of 4m interval are extracted from the finished ground surface generated from the CIVIL 3D design software.

Table 3-1 Flow path elevation and the chainage

Chainage of Drainage Flow Path (m)	Flow path Elevation (m)
0	6.92
4	6.887
8	6.855
12	6.828
16	6.805
20	6.782
24	6.76
28	6.741
32	6.719
36	6.697
40	6.663
44	6.627

Flow path profile is plotted and shown in the Figure 3-5

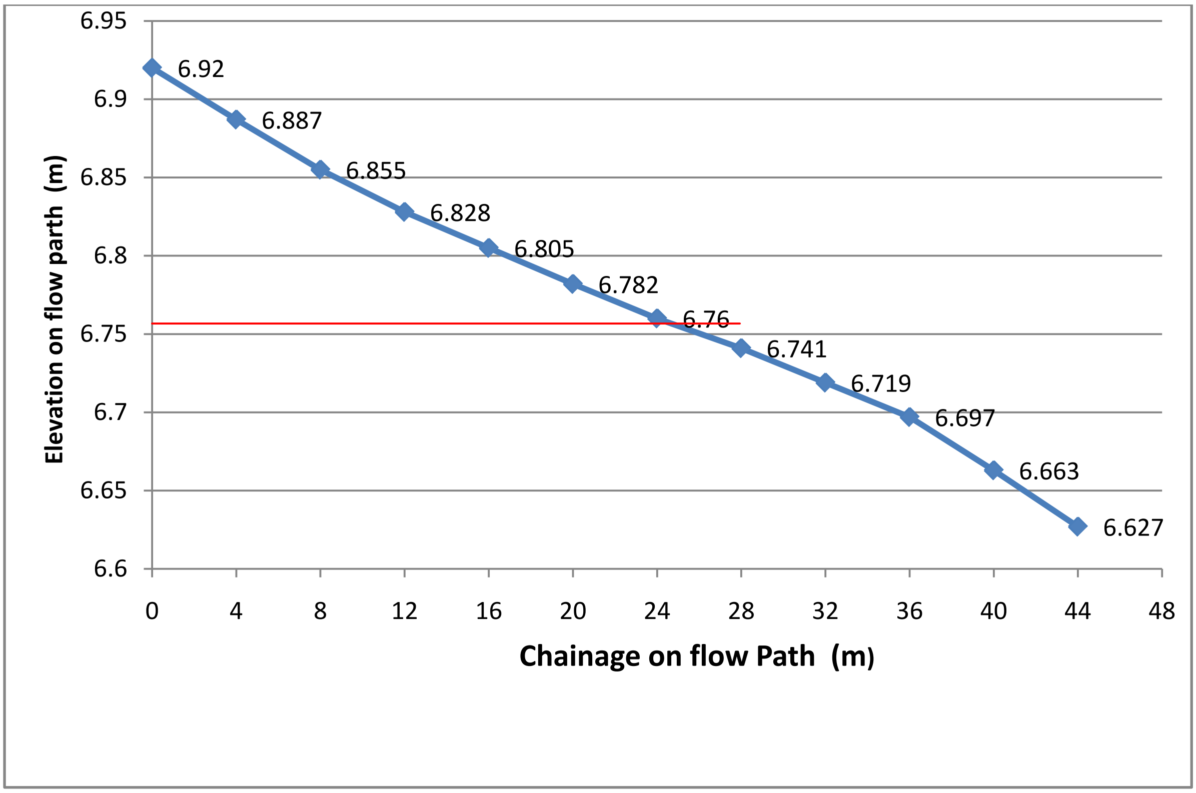


Figure 3-5 Drainage flow path

Equal area slope is calculated for the point of analysis as shown in the Figure 3-6

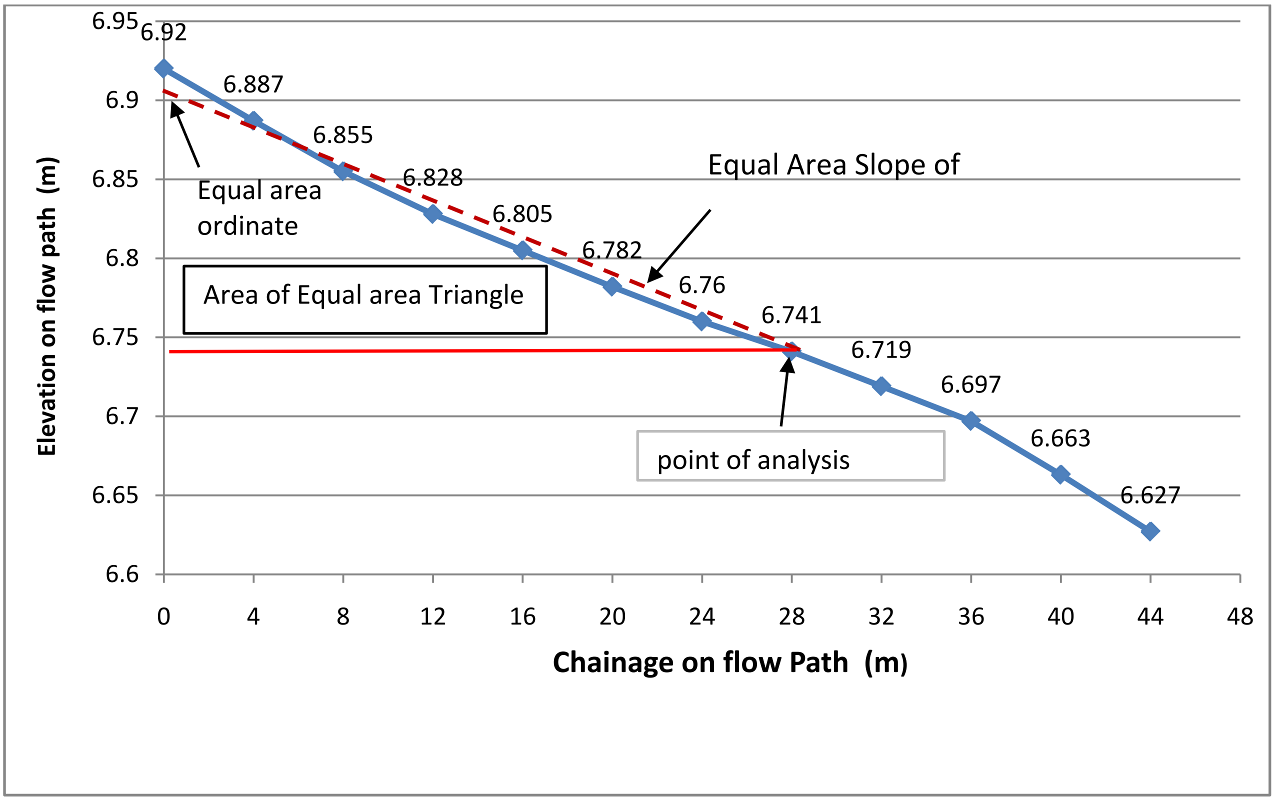


Figure 3-6Equal area slope

Area under the drainage flow path at 28m = $2.242\ m^2$

Vertical Height of equal area triangle $= \frac{2.242*2}{28}$

= 0.160m

Equal area ordinate = 0.160m+6.741m

= 6.901m

Equal area Slope (S) $= \frac{0.160}{28} * 100$

= <u>0.572%</u>

Then the equal area slopes (S) are calculated for the each point of analysis in the interval of 4m.

Table 3-2 Equal area slope along the drainage flow path

Chainage of Drainage Flow Path (m)	Flow path Elevation (m)	Difference in elevation (m)	Total Area of Equal area Triangle (m^2)	Height of equal area triangle (m)	Equal area ordinate (m)	Equal area slope (%)
0	6.92	-	-	-	-	-
4	6.887	0.033	0.066	0.033	6.920	0.825
8	6.855	0.032	0.258	0.064	6.920	0.806
12	6.828	0.027	0.528	0.088	6.916	0.733
16	6.805	0.023	0.85	0.106	6.911	0.664
20	6.782	0.023	1.264	0.126	6.908	0.632
24	6.76	0.022	1.748	0.146	6.906	0.607
28	6.741	0.019	2.242	0.160	6.901	0.572
32	6.719	0.022	2.902	0.181	6.900	0.567
36	6.697	0.022	3.65	0.203	6.900	0.563
40	6.663	0.034	4.942	0.247	6.910	0.618
44	6.627	0.036	6.454	0.293	6.920	0.667

3.2.2 Calculation of Water Film Depth

Using the Gallaway Formula the water film depth (D) is calculated for the rainfall intensity (I) of 50 mm/hr.

Table 3-3 Water film depth along the drainage flow path

Chainage of Drainage Flow Path (m), **L**	Pavement Texture Depth (mm), **T**	Rainfall Intensity (mm/h),**I**	Equal area slope (%) **S**	WFD (mm)
0	0.4	50		0
4	0.4	50	0.825	1.44
8	0.4	50	0.806	2.11
12	0.4	50	0.733	2.71
16	0.4	50	0.664	3.26
20	0.4	50	0.632	3.72
24	0.4	50	0.607	4.13
28	0.4	50	0.572	4.56
32	0.4	50	0.567	4.88
36	0.4	50	0.563	5.16
40	0.4	50	0.618	5.20
44	**0.4**	**50**	0.667	5.25

Same calculation procedure is continued for all other drainage flow paths covering the study area and corresponding water film thicknesses are find out in 4m interval along the drainage path.

These steps are followed for rainfall intensities of 100 mm/hr, 150 mm/hr and 200 mm/hr

3.2.3 Contour Plans of Flow Depth for Different Rainfall Intensities.

All the water film depths values are imported to the design plan in CIVIL 3D format and contour plan of the flow depths are plotted for the rainfall intensity of 50mm/hr. Following figure shows the contour plan and the equivalent design data of the section.

I = 50mm/hr

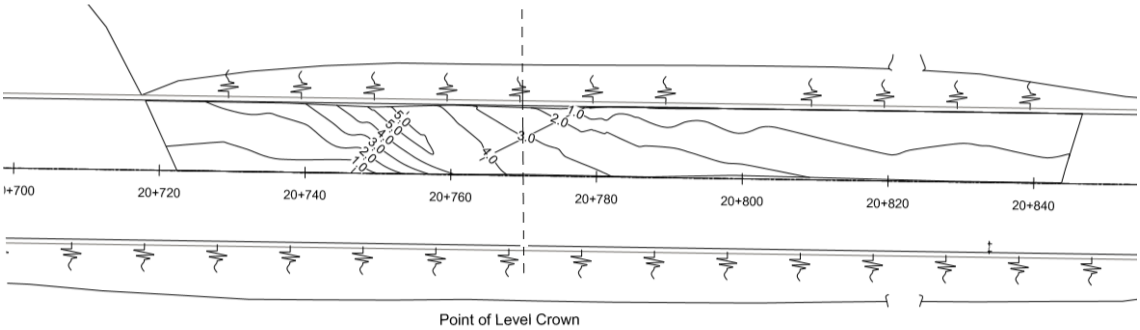


Figure 3-7 Contour plan of WFD for rainfall Intensity of 50mm/hr

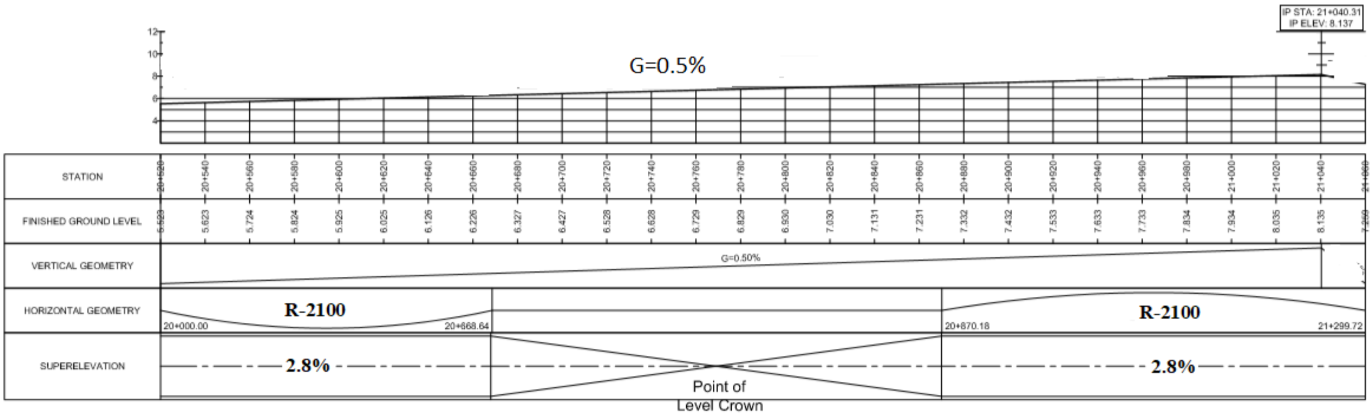


Figure 3-8 Design details of the road section

I = 100mm/hr

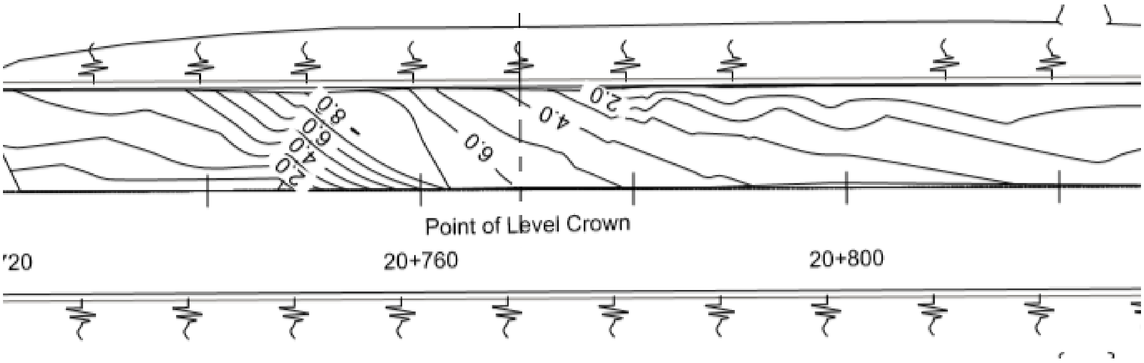


Figure 3-9 Contour plan of WFD for rainfall Intensity of 100mm/hr

I = 150mm/hr

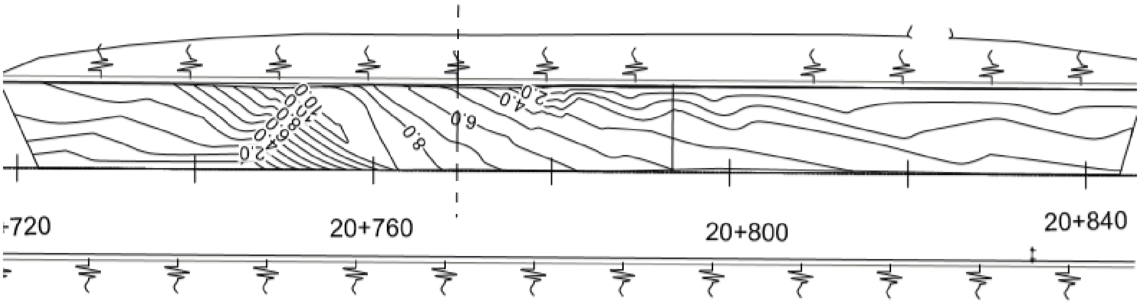


Figure 3-10 Contour plan of WFD for rainfall Intensity of 150mm/hr

I = 200mm/hr

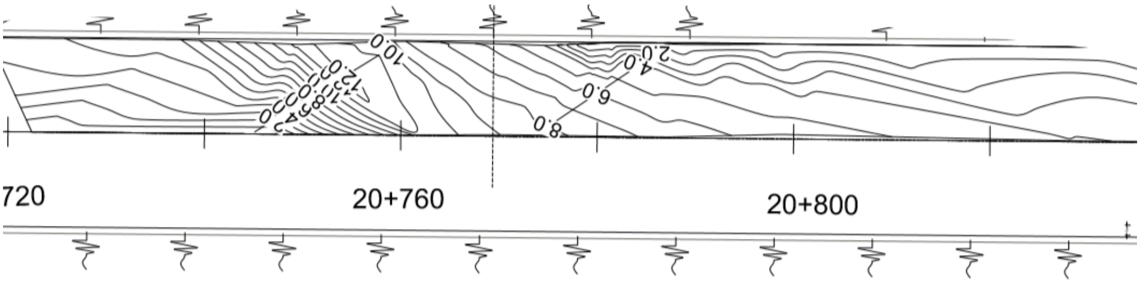


Figure 3-11Contour plan of WFD for rainfall Intensity of 200mm/hr

3.3 Calculation of Water Film Depths using Road Research Laboratory (RRL) Method

Water film thicknesses calculated above for the different rainfall intensities are again estimated with the RRL method which is developed by Road Research Laboratory in the UK in 1968.

Equation developed by RRL to estimate the WFT d as follows,

$$d = 0.046 \frac{(L_f I)^{\frac{1}{2}}}{S_f^{\frac{1}{5}}} \qquad \text{……………….(3.2)}$$

Where d = Depth of flow or water film thickness (mm) at the end of the flow path

L_f = Length of flow path (m)

I = Rainfall intensity (mm/hr)

S_f = Flow path slope

$$S_f = (S_l^{\,2} + S_c^{\,2})^{\frac{1}{2}} \qquad \text{……………….(3.3)}$$

Where S_l = Longitudinal slope (grade)

S_c = Cross fall of pavement

3.3.1 Calculation of WFT for Rainfall Intensity of 50mm/hr

Drainage flow paths developed for the Gallaway method calculation is used in this estimation. Water film depths calculated along the one of the flow path as follows.

Table 3-4Water film depth along the drainage flow path (RRL Method)

chainage of Drainage flow path (m) (L_{f})	Rainfall Intensity mm/hr (I)	Longitudinal slope (S_l)	Cross Fall (Sc)	Flow Path Slope (Sf)	WFT (mm) (d)
0	50	0.005	-	-	0
4	50	0.005	0.005	0.0068	1.77
8	50	0.005	0.003	0.0060	2.56
12	50	0.005	0.002	0.0056	3.18
16	50	0.005	0.001	0.0052	3.72
20	50	0.005	0.000	0.0050	4.20
24	50	0.005	0.001	0.0051	4.59
28	50	0.005	0.002	0.0053	4.91
32	50	0.005	0.003	0.0057	5.18
36	50	0.005	0.004	0.0061	5.41
40	50	0.005	0.005	0.0068	5.59
44	50	0.005	0.005	0.0074	5.76

These calculations are performed for all the drainage flow paths to develop the contour plan of the WFT. Same procedure is follows for the estimation of WFT and formation of contour maps for the other rainfall intensities (100, 150, and 200mm/hr)

3.3.2 Contour Maps for Different Rainfall Intensities

The contour maps generated for WFT for different rainfall intensities are as follows.

I = 50mm/hr

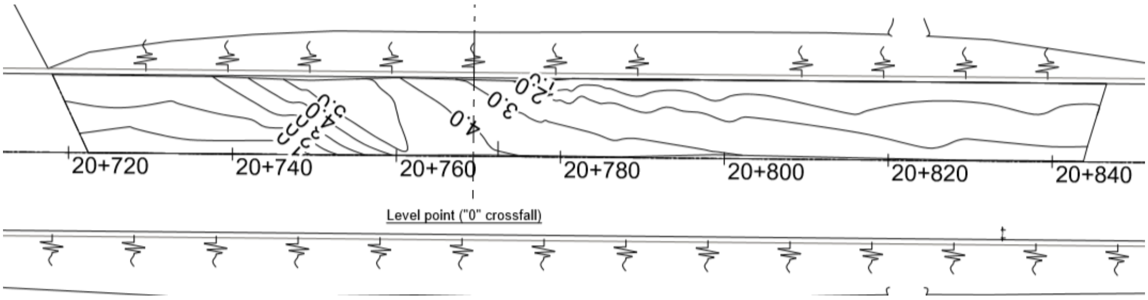


Figure 3-12 Contour plan of WFD for rainfall Intensity of 50mm/hr

I = 100mm/hr

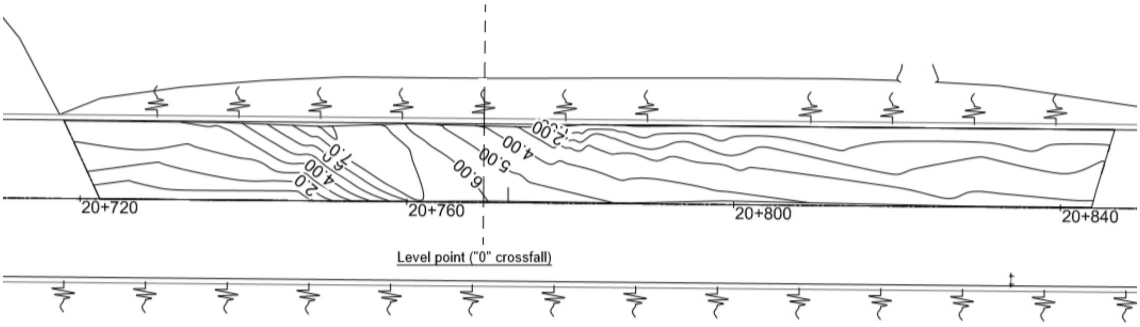


Figure 3-13 Contour plan of WFD for rainfall Intensity of 100mm/hr

I = 150mm/hr

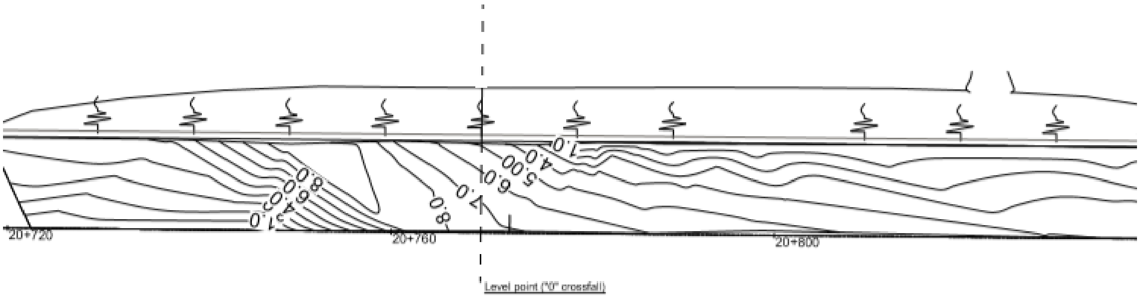


Figure 3-14 Contour plan of WFD for rainfall Intensity of 150mm/hr

I = 200mm/hr

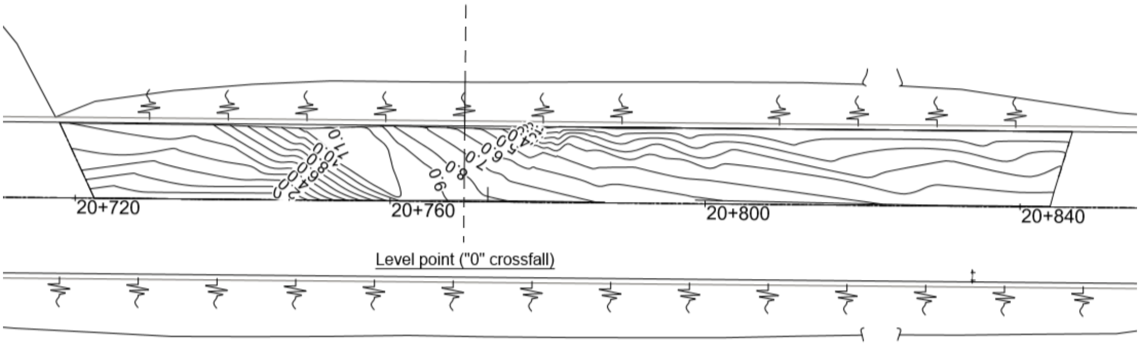


Figure 3-15 Contour plan of WFD for rainfall Intensity of 200mm/hr

3.4 Methodology (For Normal curve)

Section from Chainage 21+982 to 22+182 of southern expressway is another problematic section in the wet condition having the superelevation transition region of a normal curve with radius of 2110m. Estimation of water film depths is done for this section as follows.

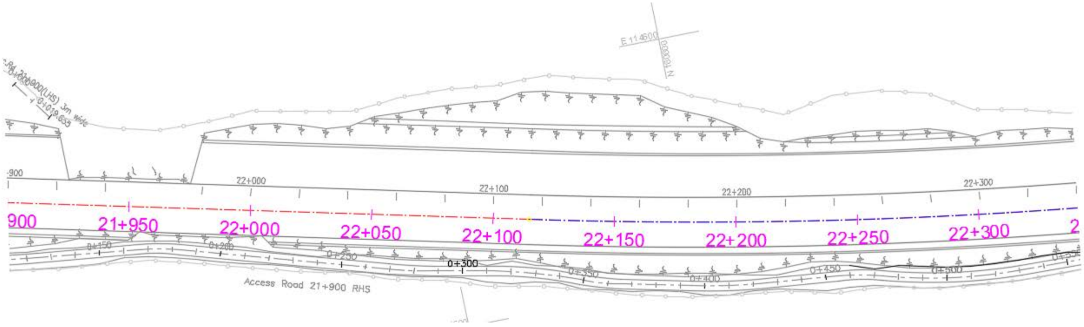


Figure 3-16Plan view of the study location

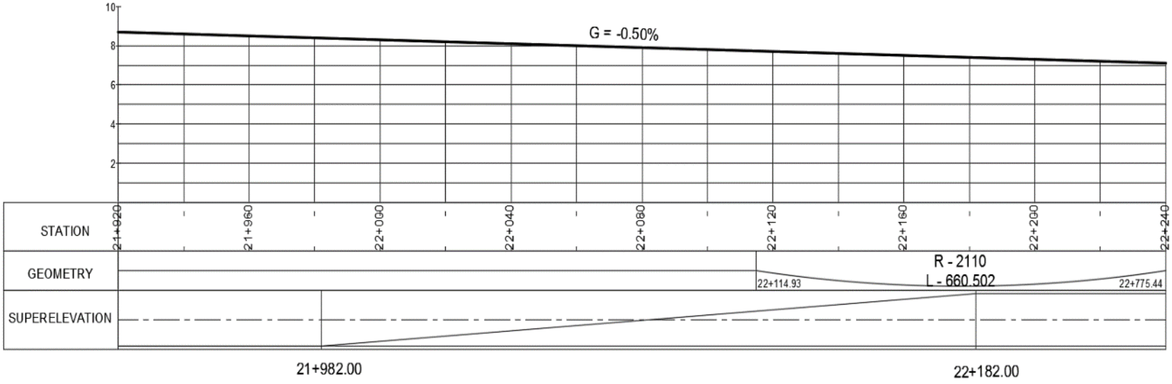
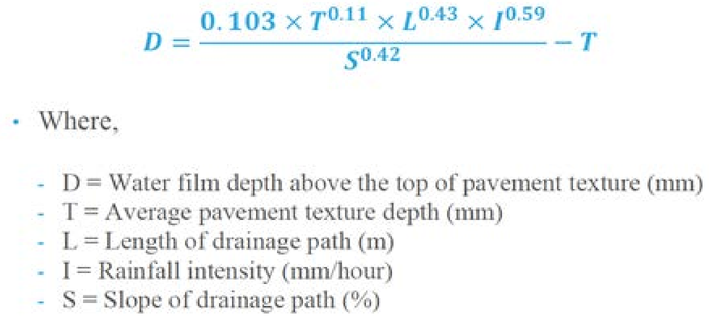


Figure 3-17Longitudinal Profile of the study location

Finding the Variables of the Gallaway equation



$$D = \frac{0.103 \times T^{0.11} \times L^{0.43} \times I^{0.59}}{S^{0.42}} - T$$

- Where,
  - D = Water film depth above the top of pavement texture (mm)
  - T = Average pavement texture depth (mm)
  - L = Length of drainage path (m)
  - I = Rainfall intensity (mm/hour)
  - S = Slope of drainage path (%)

Step 1 Pavement texture depth (T)

The observed average texture depth is **0.4mm.**

Step 2 Calculation of Drainage paths Length, (L)

The following diagram shows the drainage paths drawn for the study area for the normal curve.

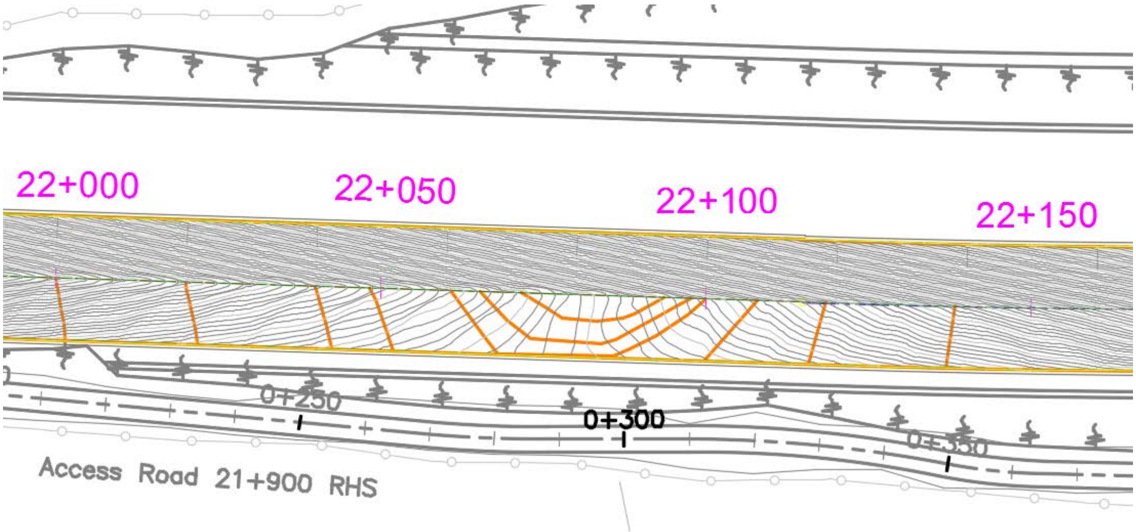


Figure 3-18 Drainage flow paths

Step 3 Estimation of slope of the drainage path (S)

The slope of drainage flow paths are calculated from the data extracted from the CIVIL 3D design drawing and using equal area method as previously calculated for the case of reverse curve.

Table 3-5Equal area slope along the drainage flow path

Chainage of Drainage Flow Path (m)	Flow path Elevation (m)	Difference in elevation (m)	Total Area of Equal area Triangle (m^2)	Height of equal area triangle (m)	Equal area ordinate (m)	Equal area slope (%)
0	8.01		-	-	-	-
4	7.978	0.032	0.064	0.032	8.010	0.800
8	7.953	0.025	0.214	0.053	8.007	0.669
12	7.937	0.016	0.374	0.062	7.999	0.519
16	7.927	0.01	0.514	0.064	7.991	0.402
20	7.918	0.009	0.676	0.068	7.986	0.338
24	7.907	0.011	0.918	0.076	7.984	0.319
28	7.898	0.009	1.152	0.082	7.980	0.294
32	7.887	0.011	1.482	0.093	7.980	0.289
36	7.87	0.017	2.06	0.114	7.984	0.318
40	7.848	0.022	2.896	0.145	7.993	0.362
44	7.828	0.02	3.736	0.170	7.998	0.386
46	7.815	0.013	4.321	0.188	8.003	0.408

3.4.1 Calculation of WFD

Gallaway Formula is used to calculate the WFD for the rainfall intensity (I) of 200 mm/hr.

Table 3-6 Water film depth along the drainage flow path

Chainage of Drainage Flow Path (m), **L**	Texture Depth (mm), **T**	Rainfall Intensity (mm/h),**I**	Equal area slope (%) **S**	WFD (mm)
0	0.4	200		0
4	0.4	200	0.800	3.83
8	0.4	200	0.669	5.74
12	0.4	200	0.519	7.73
16	0.4	200	0.402	9.85
20	0.4	200	0.338	11.73
24	0.4	200	0.319	13.05
28	0.4	200	0.294	14.47
32	0.4	200	0.289	15.45
36	0.4	200	0.318	15.63
40	0.4	200	0.362	15.48
44	0.4	200	0.386	15.71
46	0.4	200	0.408	15.63

Contour plan of the water film depths is developed as performed for reverse curve after calculating the depths for all drainage flow paths.

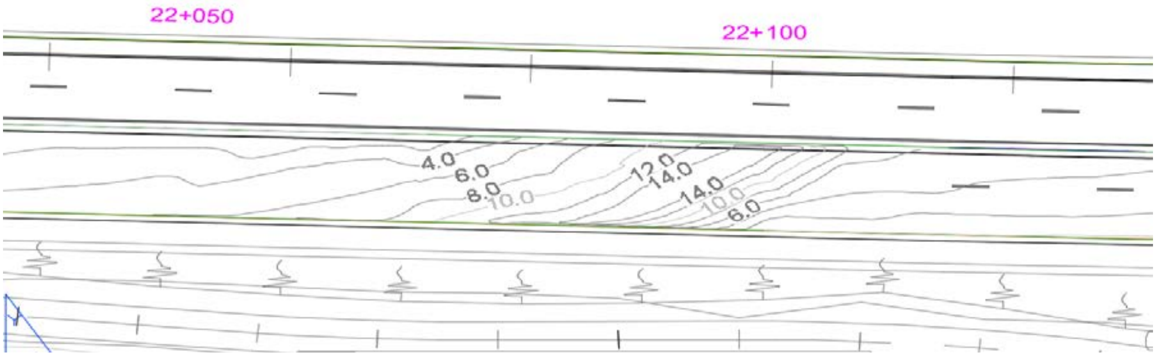


Figure 3-17 Contour plan of WFD for rainfall Intensity of 200mm/hr

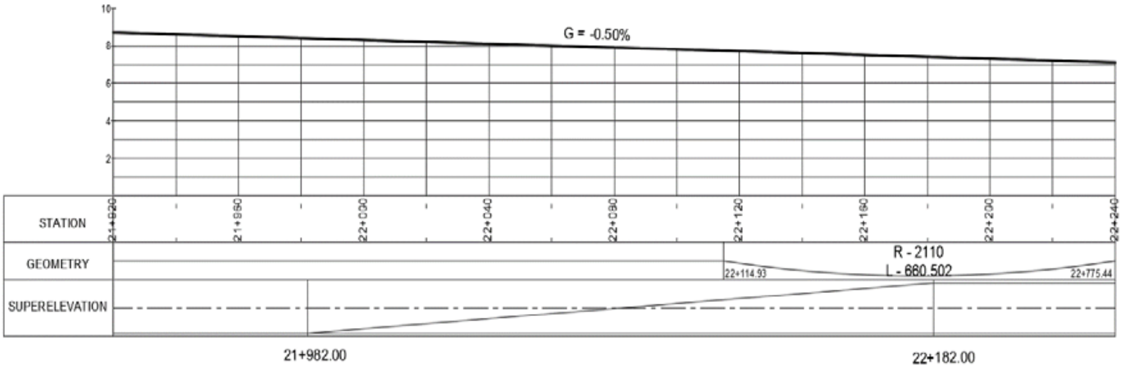


Figure 3-20 Longitudinal Profile of the study location

CHAPTER 4

4 ANALYSIS

4.1 Comparison of Water Film Depths Calculated from Gallaway Method and RRL Method.

It is shown that the contour maps developed for the water film thicknessesusing the Gallaway and RRL methods are almost same for selected rainfall intensity. Hence it can be conclude that the hydroplaning risk areas of the study section are not depending on the method that used to estimate the water film thickness.

4.2 Hydroplaning Speed and Surface Water Depth

The following figure shows the relationship between the hydroplaning speed and the accumulated surfaceWFD.

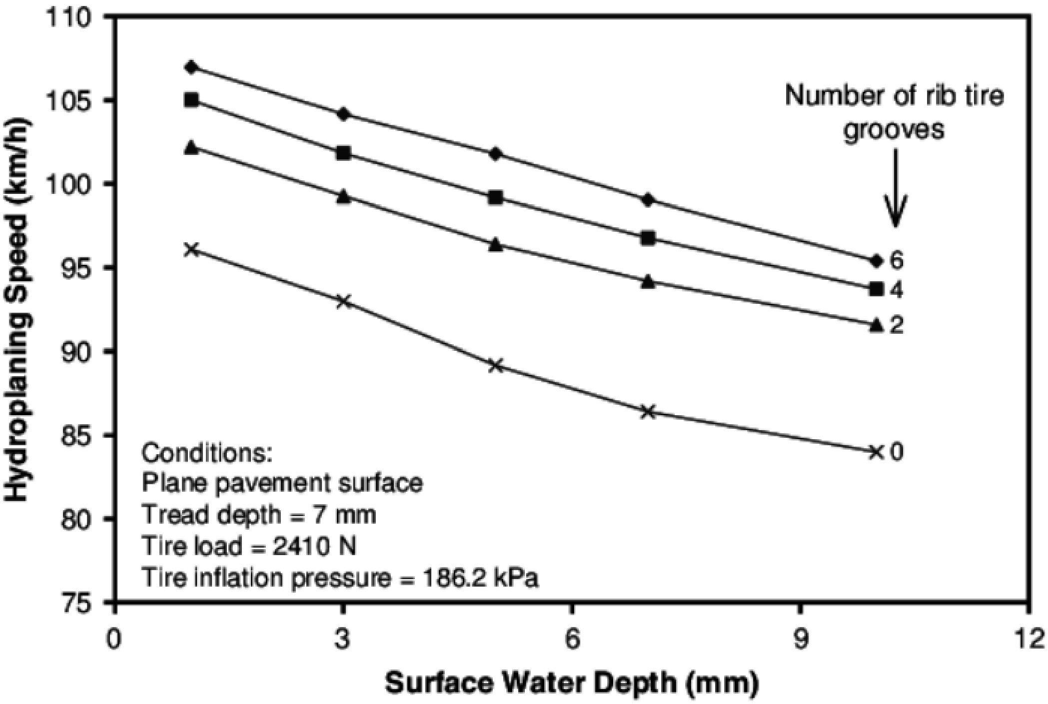


Figure 4-1 Hydroplaning Speed corresponding to surface water depth

(Source :Analytical Modeling of Effects of Rib Tires on Hydroplaning –Transport Research Board December 2008)

4.3 Identification of Hydroplaning Risk Areas.

Hydroplaning risk areas of the selected road section are identified based on the speed exceedance ratio.

$$\text{Exceedance ratio} = \frac{\text{Operational Speed}}{\text{Hydroplaning Speed}}$$

According to the exceedance ratio (ER) the following judgements can be made.

ER > 1.1 - High risk area

1.1> ER >1.0 – Medium risk area

1.0 > ER > 0.8 – Low risk area

4.3.1 Identification of Hydroplaning Risk Areas for operational speed of 100km/h.

Following table shows the Exceedance ratio for operational speed of 100km/h. The hydroplaning speed is extracted from the chart given in figure 4.1 the case of none rib tyre groove, which is more conservative.

Table 4-1Exceedance ratio for 100 km/h

WFT (mm)	Hydroplaning Speed (km/h)	Operational Speed (km/h)	Exceedance Ratio
1	97	100	1.03
2	95	100	1.05
3	93	100	1.08
4	91	100	1.10
5	89	100	1.12
6	88	100	1.14
7	87	100	1.15
8	86	100	1.16
9	85	100	1.18
10	84	100	1.19
11	83	100	1.20
12	82	100	1.22

As the rainfall intensity applicable for the road drainage design for Sri Lankan condition is 194 mm/h, the analyzed case for rainfall intensity of 200mm/h is selected for identifying the hydroplaning risk areas.

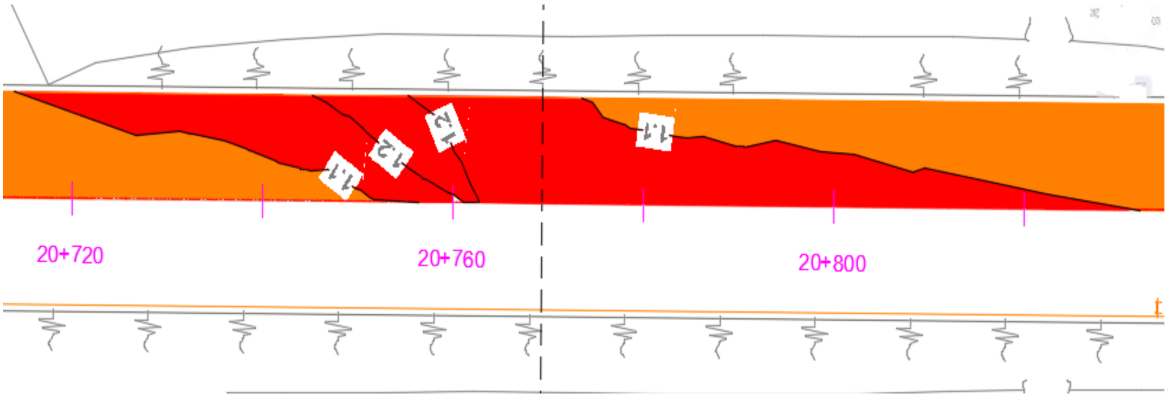


Figure 4-2 Risk Contour plan based on exceedance ratio for operational speed of 100km/h

4.3.2 Identification of Hydroplaning Risk Areas foroperational speed 90km/h.

Table 4-2Exceedance ratio for 90 km/h

WFT (mm)	Hydroplaning Speed (km/h)	Operational Speed (km/h)	Exceedance Ratio
1	97	90	0.93
2	95	90	0.95
3	93	90	0.97
4	91	90	0.99
5	89	90	1.01
6	88	90	1.02
7	87	90	1.03
8	86	90	1.05
9	85	90	1.06
10	84	90	1.07
11	83	90	1.08
12	81	90	1.11

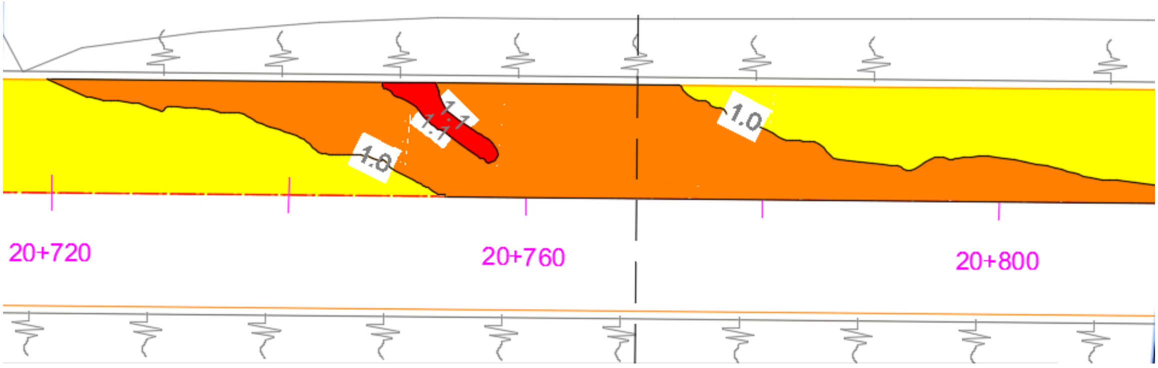


Figure 4-3 Risk Contour plan based on exceedance ratio for operational speed of 90 km/h

4.3.3 Exceedance ratios foroperational speed 80 km/h, 70 km/h and 60 km/h.

Table 4-3Exceedance ratio for 80,70 and 60 km/h

WFT (mm)	Exceedance Ratio for 80km/h	Exceedance Ratio for 70km/h	Exceedance Ratio for 60km/h
1	0.82	0.72	0.62
2	0.84	0.74	0.63
3	0.86	0.75	0.65
4	0.88	0.77	0.66
5	0.90	0.79	0.67
6	0.91	0.80	0.68
7	0.92	0.80	0.69
8	0.93	0.81	0.70
9	0.94	0.82	0.71
10	0.95	0.83	0.71
11	0.96	0.84	0.72
12	0.98	0.85	0.73

All the values of exceedance ratio for the operational speed of 80 km/h are lesser than 1.0. Hence it can be conclude that there is low risk in this case. For the 60km/h of operational speed has very less hydroplaning risk and for 70km/h is in between.

4.3.4 Identification of Hydroplaning Risk Areas at normal curve for operational speed of 100km/h.

Contour plan of exceedance ratio for the 100km/h is developed and shown in the figure 4-4

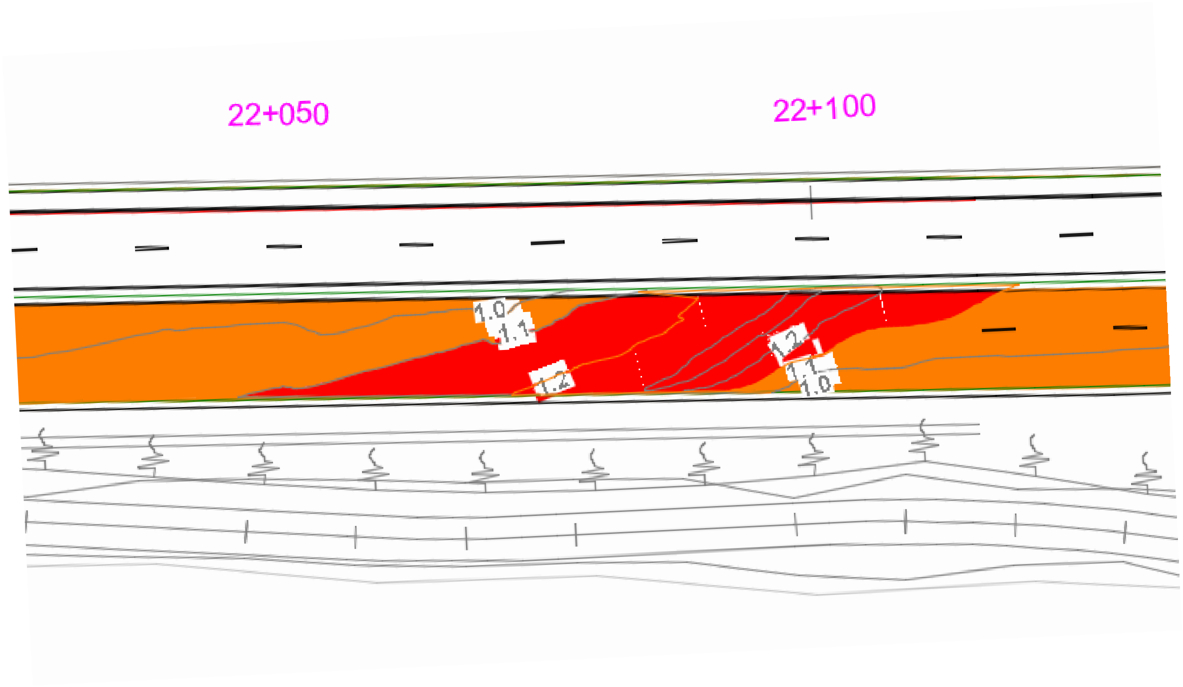


Figure 4-4 Risk Contour plan based on exceedance ratio for operational speed of 100km/h

4.3.5 Identification of Hydroplaning Risk Areas foroperational speed 90km/h.

Figure 4-5 shows the hydroplaning risk areas for the operational speed of 90km/h

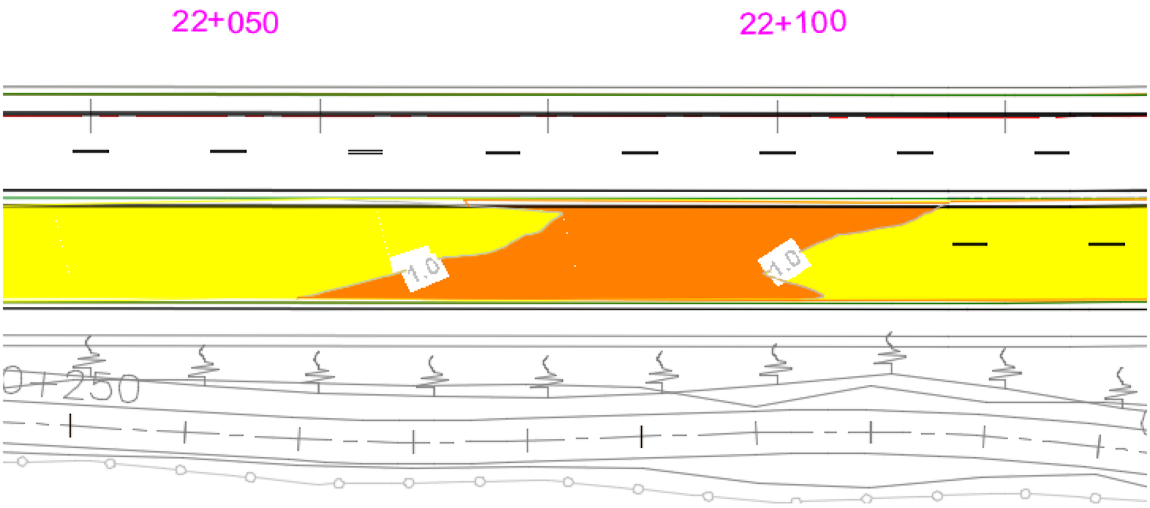


Figure 4-5 Risk Contour plan based on exceedance ratio for operational speed of 90km/h

CHAPTER 5

5 CONCLUSIONS AND RECOMMENDATIONS

This research is aimed at study on dynamic hydroplaning effect on Southern Express way. The analyzed section includes the superelevation transition section of two reverse curves. The findings can be applied for the any other similar section of expressways in Sri Lanka.

The analysis shows that hydroplaning risk area is very high at the operating speed of 100 km/h. and it is drastically reduced at the speed of 90 km/h. but there is a portion of having high risk and majority of medium risk area. It can be concluded that the operating speed of 60 km/h is a safe speed in the event of hydroplaning effect.

It can be introduced the methods of reducing hydroplaning effectfor high hydroplaning risk areas as identified in this study.

Groove cutting is a possible solution that can be implemented in this identified area and the improvement can be observed by re analyzing the case with surface grooving.

Based on the identified risk areas, the surface texture depth can be increased to reduce the hydroplaning risk and improvement can be quantified by analysis. Use of porous materials for pavement surface with the subsurface drainage is another solution that can be introduced for this particular section to minimize the hydroplaning risk.

Gradient of the road considered in this study is 0.5%. This value should be maintained as minimum value of the gradient in the superelevation transition regions. Otherwise the risk area and its severity are increased.

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