A statistical analysis of rapid deterioration of rutting and roughness of flood affected pavements in Queensland

Author

Sultana, Masuda, Chai, Gary, Martin, Tim, Chowdhury, Sanaul, Anissimov, Yuri

Published

2016

Conference Title

27th ARRB Conference: Linking People, Places and Opportunities

Version

Version of Record (VoR)

A STATISTICAL ANALYSIS OF RAPID DETERIORATION OF RUTTING AND ROUGHNESS OF FLOOD AFFECTED PAVEMENTS IN QUEENSLAND

Masuda Sultana, Gary Chai, Tim Martin, Sanaul Chowdhury and Yuri Anissimov, Griffith School of Engineering, Griffith Sciences, Griffith University, QLD 4222, Australia and ARRB Group Ltd, Melbourne, VIC 3133, Australia.

ABSTRACT

Floods can accelerate the deterioration of structural and surface conditions of pavements. The main aim of this study were to (i) statistically assess the rapid deterioration of rutting and roughness of flood affected pavements of Queensland and (ii) categorize them based on their pre-flood rutting values. An extensive statistical analysis and comparison of the pre- and post-flood data of flood affected pavements, managed by the Department of Transport and Main Roads (TMR), Queensland, shows significant increases in rutting and roughness values following flooding events between 2010 and 2015. It was identified that the pre-flood rutting is one of the main factors that contribute to and control the increase in the post-flood rutting values. Flood affected pavements were categorized into six groups based on their pre-flood rutting values to test the influence of the pre-flood rutting on increases in the post-flood rutting and roughness. The six groups are as follows: pre-flood rutting upto 4 mm, 4.1 mm to 8 mm, 8.1 mm to 12 mm, 12.1 mm to 16 mm, 16.1 mm to 20 mm and greater than 20 mm. Nine thousand pavement sections (each 100 m length) with pre-flood rutting lower than post-flood rutting were included in the analysis. These road sections were selected from approximately 21,450 TMR flood affected road sections which had both pre- and post-flood rutting and roughness data.

The analysis indicates that roads with lower pre-flood rutting are highly likely to have lower post-flood rutting and roughness values. Roads with higher pre-flood rutting are at risk of deterioration and thus increase the cost of road rehabilitation. Hence, flooding accelerates the deterioration of pavements and will continue to increase the cost of road rehabilitation/repair in future. Road agencies either need to build flood resilient roads in flood prone areas or maintain such roads with great care if building resilience in existing roads is not a cost-effective option.

INTRODUCTION

In recent years, from 2010 to 2015, extreme weather events such as frequent extreme heavy rainfall and flooding have occurred recurrently in Queensland. Recently, every continent except Antarctica has seen record-breaking floods. Rains submerged one-fifth of Pakistan, a thousand-year deluge swamped Nashville while southern France, Sri Lanka, and South Africa have had severe floods, too (Condric and Stephenson 2013). Hurricanes Katrina and Rita devastated New Orleans and south-eastern and south-western Louisiana, USA, severely damaging the infrastructure including roads (Gaspard et al. 2007). The severity of the extreme weather events has continuously raised new challenges for the state and local government agencies (Sultana et al. 2014). Studies by Sultana et al. (2014, 2015 and 2016) suggested that flood affected pavements may endure a rapid deterioration phase following a major flooding event. During the rapid deterioration phase, which starts immediately after the flood, accelerated reduction in structural condition and increases in surface condition occurred faster than expected during the original design of pavements. Chen and Zhang (2014) mentioned that there was increased damage to highways as a result of heavy trucking or vehicle loading to transport the vast amounts of debris following Hurricanes Katrina and Rita in Greater New Orleans, USA. In addition, the study also identified an escalation in deterioration as subgrade components may have been further weakened as roadways were submerged in water for extended periods of time (Chen and Zhang 2014).

Every flood causes damage to roads to some extent and increases the cost of rehabilitation. It is imperative to update the future rehabilitation and maintenance strategies of flood affected pavements to reflect the effect of rehabilitation if it was not considered in their original design. The unprecedented number of natural disasters from 2010 to 2015 caused extensive damage to communities and key road, rail, ports and waterway infrastructure. Between 2010 and 2013, the Department of Transport and Main Roads (TMR), Queensland, reconstructed large sections of the state-controlled road network through the Transport Network Reconstruction Program (TNRP) (TMR 2016). Reconstruction works costing approximately $6.4 billion were completed on approximately 8741 km of the state-controlled road network. This included approximately 1733 structures such as bridges and culverts, approximately 1421 locations requiring earthworks and batters and approximately 3335 locations needing silt and debris cleared (TMR 2015).

TMR collects surface condition data (for example roughness, rutting and cracking) at the network level. This current study analysed the rapid deterioration of rutting and roughness of Queensland roads following the flooding in 2010, 2011 and 2013. In this study, flood affected pavement section refers to the pavement sections that were included in the Transport Network Reconstruction Program (TNRP) of TMR for rehabilitation after the flood. These sections were flooded to some extent and/or damaged and rehabilitated after the flooding events. The rehabilitation date of every road was checked for analysis. Hence, the main aims of this study were to (i) assess the rutting and roughness of flood affected pavements and (ii) categorize these pavements based on their pre-flood rutting values.

An extensive statistical analysis of flood affected Queensland roads shows significant increases in deterioration of rutting and roughness following the flooding events in recent years. After comparing the frequency of data, distribution of data and range of highest and lowest point of pre- and post-flood rutting and roughness values, it was identified that the pre-flood rutting is one of the main factors that contribute to and control the increase in the post-flood rutting. Flood affected pavements were categorized into six groups based on their pre-flood rutting values to test the influence of pre-flood rutting on post-flood rutting values. The six groups are as follows: pre-flood rutting upto 4 mm, 4.1 mm to 8 mm, 8.1 mm to 12 mm, 12.1 mm to 16 mm, 16.1 mm to 20 mm and greater than 20 mm. Independent samples t test was used to compare the six groups of roads based on their pre-flood rutting values. Nine thousand road sections (each 100 m length) with pre-flood rutting values lower than post-flood rutting values were included in the analysis. These road sections were selected from 21,450 TMR flood affected pavement sections which had both pre- and post-flood rutting and roughness data. The analysis indicates that roads with lower pre-flood rutting are highly likely to have lower post-flood rutting and roughness. Roads with higher pre-flood rutting are at more risk of deterioration and increase the cost of road rehabilitation.

Flooding accelerates the deterioration of pavements and will continue to increase the cost of repair or rehabilitation of roads in future. Road agencies either need to build resilient roads in flood prone areas or maintain such roads with great care if building resilience in existing roads is not a cost-effective option. A detailed assessment of the performance of flood affected pavements is crucial for the development of accurate and reliable deterioration models for these pavements. Although this paper did not include any modelling, developing models for increases in rutting and roughness of flood affected pavements is included in the future scope of this research project. Moreover, outcome of this study will be helpful to identify and include pre-flood rutting in prediction and modelling of post-flood rutting of flood affected pavements in future.

Literature Review

An essential component of any pavement management system (PMS) is the condition prediction. Before pavement maintenance strategies and repair budgets can be prepared or effectively evaluated, pavement managers must assess the current and future condition of their pavement network. Accurate predictions are essential for budget forecasting and work planning (Shahin et al. 1994). Monitoring the pavements in flood affected areas is imperative to understand the deterioration of pavements under flooding conditions. Modelling the rapid deterioration of such pavements is also important to avoid long term consequences of not including flooding impacts in the PMS (Sultana et al. 2016). A number of unknowns exist in regard to the aftermath of flooding events on pavements, for example (Sultana et al. 2016):

- The impact of the gradual rise of flood water on the pavement and subgrade as they are saturated at that time.
- The impact of allowing traffic to travel on the roads immediately after the flood water recedes.
- The impact of heavy trucks, removing debris following flood events, on a lightly trafficked road, which was not designed to carry such loads under these conditions.

When a road is inundated, especially for a long time, the materials in the pavement become saturated. This reduces the strength of the pavement material. TMR undertakes inspections and testing to re-open the roads as soon as possible after inundation. Roads that have been saturated must be carefully managed. To do this, road closures, load restrictions and traffic management are the only options available (TMR 2014). In unbound pavement materials, prolonged exposure to excess moisture results in moisture-accelerated distresses. These distresses are primarily initiated by factors other than moisture (e.g. traffic loading). The rate of deterioration is accelerated by the presence of moisture. Prolonged exposure to excess moisture may lead to low subgrade bearing capacity, reduction in stiffness of unbound granular layers, degradation of material quality and loss of bonding between the pavement layers (Salour and Erlingsson 2014). It is often possible to identify moisture-related distress in the existing pavement during a visual survey. Examples of distress caused by the ingress of water are as follows (TMR 2012):

- in pavements with asphalt layers, stripping, rutting, loss of surface shape (depressions), fatigue cracking and potholes and
- in rigid (concrete) pavements, pumping, the formation of voids, cracking, joint deterioration and corner breaks.

Rutting is a longitudinal deformation (depression) located in wheel paths and is commonly found in flexible pavements. Generally, the layer(s) suffering the deformation will be evident from the associated indicators, or may be determined by inspection of test pits or trenches that reveal the pavement (cross) section through (across) the rut(s) (TMR 2012). One of the criterion used as part of the pavement design procedure is to limit rutting of the subgrade, or the cumulative permanent deformation caused by vertical compressive strain at the top of the subgrade layer, to a certain level. Subgrade rutting may indicate that:

- the pavement is performing in accordance with the (original) design assumptions
- the (original) design traffic has been exceeded
- the effective subgrade strength is/was less than the design strength adopted in the (original) design or
- the in situ condition of the subgrade is/was different from the design condition adopted in the (original) design (e.g. moisture content is higher) or
- the pavement has suffered from one or more overloads (e.g. an over mass vehicle traversing the pavement) (TMR 2012).

To assess whether rutting is due to inadequate pavement strength, it is useful to plot measured pavement deflections at various chainages against measured rut depths at the time of deflection testing. The higher the correlation between rut depth and deflection the more likely the rutting is at least partly due to inadequate pavement strength. If rut depths do not correlate with pavement deflection and there is little or no shoving, the most likely cause is densification of the pavement layers under traffic early in the life of the pavement (TMR 2012). Due to lack of pre- and post-flood deflection data of TMR roads, an analysis of this recommended style was not possible in this study. However, it should be noted for and considered by future studies if data are available.

Roughness is a condition parameter that characterises deviations from the intended longitudinal profile of a pavement (Austroads 2007). It is used as a measure of the rideability of the road surface (Foley 1999) and can be an indicator of the serviceability and/or structural condition of a pavement. It is influenced by surface irregularities, distortions and deformations. The roughness of a pavement usually increases with time from initial construction to ultimate retirement. It is generally assumed that as roughness increases the structural condition of the pavement decreases. In addition, as roughness increases so too does the dynamic pavement loading (TMR 2012). Measurement of roughness focuses on characteristic dimensions that affect vehicle dynamics and hence road user costs, ride quality and dynamic pavement loads (AGAM Part 5B 2007). Roughness can develop from loading of the pavement and from other factors (e.g. from material volume changes associated with moisture changes). Identifying the causes of roughness can be critical with respect to selecting an appropriate rehabilitation treatment (TMR 2012).

Road roughness is measured in terms of the International Roughness Index (commonly referred to as IRI [m/km]) for the lane (Austroads 2007). The IRI summarizes the longitudinal surface profile of the wheel path and it is computed from the surface elevation data collected by either a level survey or a multi-laser profilometer (MLP). Usually, MLP is used to measure the longitudinal profile in each wheel path with lasers. The IRI is defined by the average rectified slope (ARS), which is the ratio of the accumulated suspension motion to the distance travelled and obtained from a mathematical model of a standard quarter car traversing a measured profile at a speed of 80 km/h. It is expressed in units of meter per kilometre (m/km) (Meegoda and Gao 2014).

The progression of roughness with time is a complex phenomenon (Paterson 1987). Paterson (1987) showed that composite distress depends on deformation due to traffic loading and rut depth variation, surface defects from cracking, potholes, and patching, and a combination of aging and environmental factors. Madanat et al. (2005) analysed the roughness data from Washington State's PMS database and showed that the most relevant predictors of change in IRI for AC pavements and overlays are previous year IRI value, cumulative number of equivalent single axle loads (ESALs), base thickness, total thickness of AC, including all overlays, age of pavement, minimum temperature in the coldest month (average over the life of the pavement), and annual precipitation (average over the life of the pavement). Perera and Kohn (2001) using long-term pavement performance (LTPP) information management system (IMS) showed that design and rehabilitation parameters, climatic conditions, traffic levels, material properties, and extent and severity of distress are major factors causing changes in flexible pavement smoothness (Meegoda and Gao 2014).

Methodology and Data Collection

This study used surface condition data (rutting and roughness) of the flood affected pavement sections collected by TMR, Queensland. Initially, all pavement segments with pre- and post-flood data were screened for the analysis. The study verified a number of things while selecting pavement sections for the analysis and preparing the database for categorizing pavement sections based on their pre-flood rutting values which are discussed as follows:

- As the main aim of this study is to assess the impact of flood on pavements, road sections with both pre- and post-flood rutting and roughness data were considered for the analysis.
- Date of flooding, date of rutting and roughness data collection and rehabilitation date were recorded for the analysis.
- It was observed that post-flood rehabilitation tends to improve the road condition and such sections had a decrease in rutting and roughness values. Hence, pavement sections with post-flood data collected after the post-flood rehabilitation were not considered for the analysis as there was an improvement of the pavement condition. If such data were considered, they would create confusion in the analysis.
- It should be noted that during the analysis of individual roads and to prepare the database for categorizing the pavement sections based on pre-flood rutting values, pavement sections which had post-flood rutting values greater than pre-flood rutting were considered and

pavement sections with pre-flood rutting values greater than post-flood rutting values were discarded to avoid confusion.

SPSS (SPSS Version 22.0 2013) was used to perform the statistical analysis. It should be noted for clarity of analysis and discussion that rutting values are expressed in mm and roughness values are expressed in IRI throughout this paper.

Data Analysis and Discussion

Initially, this study checked data of approximately 58000 flood affected pavements sections (each 100 m in length) of TMR, Queensland. After checking the data, 21450 pavement sections were identified as having both pre- and post-flood rutting and roughness data. These sections included any samples with pre- and post-flood data without considering the effect of immediate repair or rehabilitation. Mean and standard deviation of rutting and roughness of the 21450 samples between 2010 and 2015 are shown in Table 1. Mean pre-flood rutting of 21450 samples is greater than mean post-flood rutting. Mean pre-flood roughness is slightly lower than mean post-flood roughness. These samples were from different flood affected pavements across Queensland. The term pre-flood indicates that these pavement sections were first flooded in either 2010 or 2011 and data were collected before flood (in the year 2009 or 2010). Rehabilitation and repair of pavements were conducted at different times from 2010 to 2013 as a part of the Transport Network Reconstruction Program (TNRP). Therefore, overall, average rutting and roughness values gradually improved in 2012, 2013, 2014 and 2015.

The data were screened again and sections with post-flood rutting values greater than pre-flood rutting values were selected resulting in 9000 road sections. Table 2 presents the mean and standard deviation of the 9000 flood affected road segments. Mean pre-flood rutting and roughness are lower than the mean post-flood rutting and roughness values. Mean rutting and roughness from 2012, 2013, 2014 and 2015, decreased due to the rehabilitation works.

Table 1: Mean and Standard Deviation of Rutting and Roughness (Criteria of sample selection: Having Pre- and Post-flood rutting and roughness data)

Variables	Sample Size (N)	Mean	Std. Deviation
Rut (Pre-flood)	21450	7.354	5.163
Rutting (Post-	21450	6.554	3.921
Rut 2012	20083	6.474	4.049
Rut 2013	18939	5.864	3.560
Ru 2014	19041	5.373	3.069
Rut 2015	14532	4.905	2.230
IRI 2010	21449	2.720	1.083
IRI 2011	21433	2.723	1.002
IRI 2012	20059	2.637	0.974
IRI 2013	19004	2.466	0.986
IRI 2014	19050	2.205	0.974
IRI 2015	14532	1.946	0.740

Table 2: Mean and Standard Deviation of Rutting and Roughness (Criteria of sample selection: Pre-flood rutting < Post-flood rutting)

Variables	Sample Size	Mean	Std
Rut (Pre-flood)	9000	5.289	3.191
Rut (Post-flood)	9000	7.277	4.308
Rut 2012	8550	6.273	4.227
Rut 2013	8121	5.810	3.762
Rut 2014	8257	5.420	2.911
Rut 2015	6198	4.934	2.181
IRI (Pre-flood)	9000	2.646	1.077
IRI (Post-flood)	8995	2.696	0.989
IRI 2012	8476	2.586	0.964

IRI 2013	8040	2.432	0.980
IRI 2014	8223	2.218	1.004
IRI 2015	6216	1.948	0.729

To analyse if flooding had significant impact on rutting and roughness, paired samples t-tests method were used. Mean of ten pairs of samples were compared which were collected from the same locations. Ten pairs of samples are described as follows:

1. Pre- and post-flood rutting
2. Post-flood rutting and rutting in 2012
3. Rutting in 2012 and 2013
4. Rutting in 2013 and 2014
5. Rutting in 2014 and 2015
6. Pre- and post-flood roughness
7. Post-flood roughness and roughness in 2012
8. Roughness in 2012 and 2013
9. Roughness in 2013 and 2014 and
10. Roughness in 2014 and 2015

The results of the paired samples t test are shown in Table 3 and 4. Table 3 indicates that each of these ten pairs of samples has significant correlation with less standard error. Significance level of each pair of samples is represented by the p-value in Table 4.

Table 3: Paired Samples Statistics of Rutting and Roughness

Pair	Variables	Mean	Sample Size (N)	Std. Deviation	Std. Error Mean	Correlation
Pair 1	Rut (Pre-	5.289	9000	3.191	0.034	0.847
	Rut (Post-	7.277		4.308	0.045	
Pair 2	Rut (Post-	7.257	8550	4.320	0.047	0.585
	Rut 2012	6.273		4.227	0.046	
Pair 3	Rut 2012	6.236	7976	4.203	0.047	0.596
	Rut 2013	5.815		3.788	0.042	
Pair 4	Rut 2013	5.770	7705	3.799	0.043	0.475
	Rut 2014	5.365		2.762	0.031	
Pair 5	Rut 2014	5.380	5751	2.945	0.039	0.503
	Rut 2015	4.931		2.158	0.028	
Pair 6	IRI (Pre-flood)	2.646	8995	1.077	0.011	0.792
	IRI (Post-	2.696		0.989	0.010	
Pair 7	IRI (Post-	2.699	8471	0.992	0.011	0.672
	IRI 2012	2.586		0.963	0.010	
Pair 8	IRI 2012	2.595	7828	0.969	0.011	0.705
	IRI 2013	2.442		0.981	0.011	
Pair 9	IRI 2013	2.397	7588	0.953	0.011	0.557
	IRI 2014	2.215		1.002	0.012	
Pair 10	IRI 2014	2.225	5730	1.075	0.014	0.495
	IRI 2015	1.954		0.729	0.010	

Statistical comparison of mean of ten pairs of samples are explained as follows:

1. Mean post-flood rutting value is significantly ($p < 0.05$) higher than mean pre-flood rutting value.
2. Mean post-flood rutting value is significantly ($p < 0.05$) higher than mean rutting value in 2012.
3. Mean rutting value in 2012 is significantly ($p < 0.05$) higher than mean rutting value in 2013.
4. Mean rutting value in 2013 is significantly ($p < 0.05$) higher than mean rutting value in 2014.
5. Mean rutting value in 2014 is significantly ($p < 0.05$) higher than mean rutting value in 2015.
6. Mean post-flood roughness value is significantly ($p < 0.05$) higher than mean pre-flood roughness value.
7. Mean post-flood roughness value is significantly ($p < 0.05$) higher than mean roughness value in 2012.
8. Mean roughness value in 2012 is significantly ($p < 0.05$) higher than mean roughness value in 2013.
9. Mean roughness value in 2013 is significantly ($p < 0.05$) higher than mean of roughness value in 2014.
10. Mean of roughness value in 2014 is significantly ($p < 0.05$) higher than mean of roughness value in 2015.

Table 4: Paired Samples Test

Pair	Variables	Paired Differences					t	degrees of freedom	p-value
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Rut (Pre-flood) & Rut (Post-flood)	-1.988	2.334	0.025	-2.036	-1.940	-80.820	8999	0.00
Pair 2	Rut (Post-flood) & Rut 2012	0.984	3.897	0.042	0.901	1.067	23.351	8549	0.00
Pair 3	Rut 2012 & Rut 2013	0.421	3.609	0.040	0.342	0.500	10.420	7975	0.00
Pair 4	Rut 2013 & Rut 2014	0.404	3.476	0.040	0.327	0.482	10.210	7704	0.00
Pair 5	Rut 2014 & Rut 2015	0.449	2.635	0.035	0.381	0.517	12.921	5750	0.00
Pair 6	IRI (Pre-flood) & IRI (Post-flood)	-0.050	0.671	0.007	-0.064	-0.036	-7.049	8994	0.00
Pair 7	IRI (Post-flood) & IRI 2012	0.113	0.792	0.009	0.097	0.130	13.182	8470	0.00
Pair 8	IRI 2012 & IRI 2013	0.154	0.748	0.008	0.137	0.170	18.151	7827	0.00
Pair 9	IRI 2013 & IRI 2014	0.183	0.921	0.011	0.162	0.204	17.297	7587	0.00
Pair 10	IRI 2014 & IRI 2015	0.271	0.955	0.013	0.247	0.296	21.515	5729	0.00

In summary, increases in mean rutting and roughness values after flood were found to be statistically significant for Queensland roads as shown by pairs 1 and 6 and pairs 2 and 7. However, pairs 3 & 8, 4 & 9 and 5 & 10 show a decrease in rutting and roughness values over an interval of one year which was mainly due to the rehabilitation of different roads from 2010 to

2015. Hence, these results indicate that flooding has a significant impact on rapid increases in rutting and roughness of Queensland roads.

In the 21,450 flood affected pavement sections, it was generally observed that the lower the pre-flood rutting values, the lower the post-flood rutting values, if there was no repair or rehabilitation work carried out immediately after the flooding. In the database (21,450 samples), 90% of samples with pre-flood rutting lower than post-flood rutting had pre-flood rutting values up to 9.4 mm and post-flood rutting values up to 12.6 mm and the remaining 10% of samples had pre-flood rutting varying from 9.5 to 28.2 and post-flood rutting varying from 12.7 to 44.7.

Differences in pre- and post-flood rutting is designated as $\Delta Rut_{post\text{-}flood}$ and differences in pre- and post-flood roughness is designated as $\Delta IRI_{post\text{-}flood}$. $\Delta Rut_{post\text{-}flood}$ and $\Delta IRI_{post\text{-}flood}$ were calculated for each sample by deducting post-flood rutting from pre-flood rutting ($\Delta Rut_{post\text{-}flood} = Rut_{post\text{-}flood} - Rut_{pre\text{-}flood}$) and post-flood roughness from pre-flood roughness ($\Delta IRI_{post\text{-}flood} = Roughness_{post\text{-}flood} - Roughness_{pre\text{-}flood}$). $\Delta Rut_{post\text{-}flood}$ for the 90% of samples were less than 4.4 mm and varied from 4.5 to 40.2 mm in the 10% samples. The 90% samples with pre-flood roughness lower than post-flood roughness, had pre-flood IRI values up to 3.63 and post-flood IRI values up to 4.13. Rest of the 10% samples had pre-flood IRI varying from 3.63 to 7.63 and post-flood IRI varying from 4.14 to 14.68. $\Delta IRI_{post\text{-}flood}$ for the 90% of samples were less than 0.74 and varied from 0.75 to 12.19 in the 10% samples.

The nine thousand samples with pre-flood rutting lower than post-flood rutting were used to categorize pavement sections into six groups based on their pre-flood rutting values which are as follows.

- Group one: Pre-flood Rutting is less than 4 mm
- Group two: Pre-flood Rutting is within the range of 4.1 mm to 8 mm
- Group three: Pre-flood Rutting is within the range of 8.1 mm to 12 mm
- Group four: Pre-flood Rutting is within the range of 12.1 mm to 16 mm
- Group five: Pre-flood Rutting is within the range of 16.1 mm to 20 mm
- Group six: Pre-flood Rutting is greater than 20 mm.

Independent samples t-tests were used to compare the mean $\Delta Rut_{post\text{-}flood}$ among the six groups of samples to test the significance of mean $\Delta Rut_{post\text{-}flood}$ (refer to Tables 5 and 6). The results are discussed as follows:

- Mean $\Delta Rut_{post\text{-}flood}$ for Group 1 is significantly ($p < 0.05$) lower than mean $\Delta Rut_{post\text{-}flood}$ for Group 2.
- Mean $\Delta Rut_{post\text{-}flood}$ for Group 2 is significantly ($p < 0.05$) lower than mean $\Delta Rut_{post\text{-}flood}$ for Group 3.
- Mean $\Delta Rut_{post\text{-}flood}$ for Group 3 is significantly ($p < 0.05$) lower than mean $\Delta Rut_{post\text{-}flood}$ for Group 4.

Table 5: Group Statistics for Independent Samples t Test to compare mean of differences in Pre- and Post-flood Rutting ($\Delta Rut_{post\text{-}flood}$)

Comparison	Name of Group	Sample Size (N)	Mean $\Delta Rut_{post\text{-}}$	Std. Deviation	Std. Error
Group 1 & 2	Pre-flood Rut <4 mm	3845	1.681	1.692	0.027
	Pre-flood Rut: 4.1 to 8 mm	3801	1.939	2.218	0.036
Group 2 & 3	Pre-flood Rut: 4.1 to 8 mm	3801	1.939	2.218	0.036
	Pre-flood Rut: 8.1 to 12 mm	961	2.762	3.392	0.109
Group 3 & 4	Pre-flood Rut: 8.1 to 12 mm	961	2.762	3.392	0.109
	Pre-flood Rut: 12.1 to 16 mm	253	3.548	3.978	0.250
Group 4 & 5	Pre-flood Rut: 12.1 to 16 mm	253	3.548	3.978	0.250
	Pre-flood Rut: 16.1 to 20 mm	89	3.813	4.084	0.433

Group 5 & 6	Pre-flood Rut: 16.1 to 20 mm	89	3.813	4.084	0.433
	Pre-flood Rut > 20 mm	33	4.282	4.676	0.814

Table 6: Independent Samples t Test to compare mean $\Delta Rut_{post\text{-}flood}$

Equal variances assumed/ Equal variances not assumed	Levene's Test for Equality of Variances		t-test for Equality of Means						
	F	Sig.	t	degrees of freedom	p-value	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
								Lower	Upper
Group 1 and 2: Pre-flood rutting less than 4 mm and 4.1 to 8 mm									
Equal variances	109.66	.00	-	7644	.000	-0.258	0.045	-	-
Equal variances not			-	7105.5	.000	-0.258	0.045	-	-
Group 2 and 3: Pre-flood rutting 4.1 to 8 mm and 8.1 to 12 mm									
Equal variances	150.46	.00	-	4760	.000	-.823	.090	-	-.646
Equal variances not			-	1175.18	.000	-.823	.115	-	-.597
Group 3 and 4: Pre-flood rutting 8.1 to 12 mm and 12.1 to 16 mm									
Equal variances	13.596	.00	-	1212	.002	-.786	.249	-	-.298
Equal variances not			-	354.305	.004	-.786	.273	-	-.249
Group 4 and 5: Pre-flood rutting 12.1 to 16 mm and 16.1 to 20 mm									
Equal variances	.010	.92	-.538	340	.591	-.266	.494	-	.705
Equal variances not			-.531	150.705	.596	-.266	.500	-	.722
Group 5 and 6: Pre-flood rutting 16.1 to 20 mm and greater than 20 mm									
Equal variances	.158	.69	-.541	120	.590	-.468	.866	-	1.247
Equal variances not			-.508	51.168	.614	-.468	.922	-	1.382

Although mean $\Delta Rut_{post\text{-}flood}$ for Group 4 is lower than the mean $\Delta Rut_{post\text{-}flood}$ for Group 5, the difference was not statistically significantly ($p > 0.05$). Mean $\Delta Rut_{post\text{-}flood}$ for Group 5 is lower than the mean $\Delta Rut_{post\text{-}flood}$ for Group 6, but the difference was not statistically significantly ($p > 0.05$). The lack of a significant result for these two comparisons could be due to the reduced number of samples as there were not many samples with the criterion of pre- and post-flood rutting >16 mm. There were only 89 samples for Group 5 (Pre-flood Rutting 16.1 mm to 20 mm) and 33 samples for Group 6 (Pre-flood Rutting greater than 20 mm) which are much smaller when compared to the other four groups (Table 6). Although there were samples with pre-flood rutting >16 mm in the rest of the 21,450 samples, the post-flood data collection was probably conducted after rehabilitation (as data showed a significant improvement in road condition post-flood). This was probably because most of the road sections with higher pre-flood rutting needed to be rehabilitated / repaired immediately after the flood and before the next survey due to the poor condition of the road.

The independent samples t-tests were used to compare the mean pre- and post-flood IRI and $\Delta IRI_{post\text{-}flood}$ for the six groups of pavements (refer to Tables 7 and 8). Mean pre- and post-flood IRI of Group 1 are significantly ($p < 0.05$) lower than the mean pre- and post-flood IRI of Group 2. Mean $\Delta IRI_{post\text{-}flood}$ of Group 1 is greater than mean $\Delta IRI_{post\text{-}flood}$ of Group 2. Mean pre- and post-flood IRI of Group 2 are significantly ($p < 0.05$) lower than mean pre- and post-flood IRI of Group 3. Mean pre-flood IRI of Group 3 is lower than mean pre- flood IRI of Group 4 but statistically not significant ($p > 0.05$). Mean post-flood IRI of Group 3 is significantly ($p < 0.05$) lower than mean post-flood IRI of Group 4. Mean $\Delta IRI_{post\text{-}flood}$ of Group 3 is lower than mean $\Delta IRI_{post\text{-}flood}$ of Group 4 but not significant ($p > 0$ .05). Mean pre- and post-flood IRI of Group 4 are lower than mean pre- and post-flood IRI of Group 5 but statistically not significant ($p > 0.05$). Mean pre- and post-flood IRI and $\Delta IRI_{post\text{-}flood}$ of Group 5 are significantly ($p < 0.05$) lower than mean pre- and post-flood IRI and $\Delta IRI_{post\text{-}flood}$ of Group 6.

Hence, it can be concluded that lower the pre-flood rutting, it is highly likely to have lower pre- and post-flood roughness. The higher the pre-flood rutting, it is highly likely to have higher pre- and post-flood roughness.

Table 7: Statistics for Independent sample t test of Pre- and Post-flood IRI and difference in Pre- and Post-flood IRI

Rutting Criteria	Variables	Group Name	Sample Size (N)	Mean	Std. Deviation	Std. Error Mean
Group 1 and 2	IRI Pre-flood	Pre-flood Rut <4 mm	3845	2.374	0.891	0.014
		Pre-flood Rut: 4.1 to 8 mm	3801	2.785	1.101	0.018
	IRI Post-flood	Pre-flood Rut <4 mm	3841	2.428	0.835	0.013
		Pre-flood Rut: 4.1 to 8 mm	3800	2.835	0.984	0.016
	$\Delta IRI_{post-flood}$	Pre-flood Rut <4 mm	3845	0.053	0.554	0.009
		Pre-flood Rut: 4.1 to 8 mm	3801	0.051	0.697	0.011
Group 2 and 3	IRI Pre-flood	Pre-flood Rut: 4.1 to 8 mm	3801	2.785	1.101	0.018
		Pre-flood Rut: 8.1 to 12 mm	961	2.966	1.212	0.039
	IRI Post-flood	Pre-flood Rut: 4.1 to 8 mm	3800	2.835	0.984	0.016
		Pre-flood Rut: 8.1 to 12 mm	961	2.977	1.017	0.033
	$\Delta IRI_{post-flood}$	Pre-flood Rut: 4.1 to 8 mm	3801	0.051	0.697	0.011
		Pre-flood Rut: 8.1 to 12 mm	961	0.015	0.742	0.024
Group 3 and 4	IRI Pre-flood	Pre-flood Rut: 8.1 to 12 mm	961	2.966	1.212	0.039
		Pre-flood Rut: 12.1 to 16 mm	253	3.073	1.504	0.095
	IRI Post-flood	Pre-flood Rut: 8.1 to 12 mm	961	2.977	1.017	0.033
		Pre-flood Rut: 12.1 to 16 mm	253	3.135	1.168	0.073
	$\Delta IRI_{post-flood}$	Pre-flood Rut: 8.1 to 12 mm	961	.0151	0.742	.02394
		Pre-flood Rut: 12.1 to 16 mm	253	.0617	0.939	.05903
Group 4 and 5	IRI Pre-flood	Pre-flood Rut: 12.1 to 16 mm	253	3.073	1.504	0.095
		Pre-flood Rut: 16.1 to 20 mm	89	3.331	1.100	0.117
	IRI Post-flood	Pre-flood Rut: 12.1 to 16 mm	253	3.135	1.168	0.073
		Pre-flood Rut: 16.1 to 20 mm	89	3.360	1.191	0.126
	$\Delta IRI_{post-flood}$	Pre-flood Rut: 12.1 to 1 6 mm	253	0.062	0.939	0.059
		Pre-flood Rut: 16.1 to 20 mm	89	0.029	0.699	0.074
Group 5 and 6	IRI Pre-flood	Pre-flood Rut: 16.1 to 20 mm	89	3.331	1.100	0.117
		Pre-flood Rut > 20 mm	33	3.910	1.529	0.266
	IRI Post-flood	Pre-flood Rut: 16.1 to 20 mm	89	3.360	1.191	0.126
		Pre-flood Rut > 20 mm	33	4.466	3.331	0.580
	$\Delta IRI_{post-flood}$	Pre-flood Rut: 16.1 to 20 mm	89	0.029	0.699	0.074
		Pre-flood Rut > 20 mm	33	0.556	2.681	0.467

Table 8: Group Statistics for Independent sample t test of Pre- and Post-flood Roughness

Rutting Criteria	Variable		Levene's Test for Equality of Variances		t-test for Equality of Means					95% Confidence Interval of the Difference	
			F	Sig.	t	Degrees of freedom	p-value	Mean Difference	Std. Error Difference	Lower	Upper
Group 1 and 2	IRI Pre-flood	Equal variances assumed	72.344	.000	-17.955	7644	.000	-.411	.023	-.456	-.366
		Equal variances not assumed			-17.933	7293.066	.000	-.411	.023	-.456	-.366
	IRI Post-flood	Equal variances assumed	75.321	.000	-19.489	7639	.000	-.407	.021	-.448	-.366
		Equal variances not assumed			-19.472	7416.202	.000	-.407	.021	-.448	-.366
	$\Delta IRI_{post-flood}$	Equal variances assumed	17.830	.000	.171	7644	.864	.002	.014	-.026	.031
		Equal variances not assumed			.170	7238.831	.865	.002	.014	-.026	.031
Group 2 and 3	IRI Pre-flood	Equal variances assumed	7.584	.006	-4.443	4760	.000	-.180	.041	-.260	-.101
		Equal variances not assumed			-4.196	1387.181	.000	-.180	.043	-.265	-.096
	IRI Post-flood	Equal variances assumed	7.193	.007	-3.977	4759	.000	-.142	.036	-.212	-.072
		Equal variances not assumed			-3.900	1448.219	.000	-.142	.036	-.214	-.071
	$\Delta IRI_{post-flood}$	Equal variances assumed	.339	.560	1.404	4760	.160	.036	.026	-.014	.086
		Equal variances not assumed			1.353	1418.313	.176	.036	.026	-.016	.088
Group 3 and 4	IRI Pre-flood	Equal variances assumed	1.054	.305	-1.195	1212	.232	-.108	.090	-.285	.069
		Equal variances not assumed			-1.055	342.958	.292	-.108	.102	-.309	.093
	IRI Post-flood	Equal variances assumed	2.364	.124	-2.128	1212	.034	-.158	.074	-.304	-.012
		Equal variances not assumed			-1.964	358.884	.050	-.158	.080	-.316	.000
	$\Delta IRI_{post-flood}$	Equal variances assumed	.017	.895	-.838	1212	.402	-.047	.056	-.156	.063
		Equal variances not assumed			-.732	339.316	.465	-.047	.064	-.172	.079
Group 4 and 5	IRI Pre-flood	Equal variances assumed	.151	.698	-1.484	340	.139	-.258	.174	-.600	.084
		Equal variances not assumed			-1.719	210.021	.087	-.258	.150	-.554	.038
	IRI Post-flood	Equal variances assumed	.673	.413	-1.556	340	.121	-.225	.145	-.510	.059
		Equal variances not assumed			-1.542	151.542	.125	-.225	.146	-.514	.063
	$\Delta IRI_{post-flood}$	Equal variances assumed	.367	.545	.301	340	.764	.033	.109	-.181	.247
		Equal variances not assumed			.346	206.195	.730	.033	.095	-.154	.220
Group 5 and 6	IRI Pre-flood	Equal variances assumed	7.170	.008	-2.310	120	.023	-.579	.250	-1.074	-.083
		Equal variances not assumed			-1.991	44.865	.053	-.579	.291	-1.164	.007
	IRI Post-flood	Equal variances assumed	7.271	.008	-2.713	120	.008	-1.106	.408	-1.913	-.299
		Equal variances not assumed			-1.863	35.078	.071	-1.106	.594	-2.311	.099
	$\Delta IRI_{post-flood}$	Equal variances assumed	9.986	.002	-1.716	120	.089	-.527	.307	-1.136	.081
		Equal variances not assumed			-1.116	33.626	.272	-.527	.472	-1.488	.433

It can be concluded that flooding had a great impact on accelerating the deterioration of surface conditions such as rutting and roughness of roads. Roads with lower pre-flood rutting are highly likely to have lower post-flood rutting and roughness. Roads with higher pre-flood rutting are highly likely to have higher post-flood rutting and roughness and are more likely to deteriorate and increase the cost of road rehabilitation. As these samples of pavement sections consist of roads across Queensland which were rehabilitated at different times from 2010 to 2015, there were significant improvements in rutting and roughness values after 2011. Individual roads should be analysed to see the impact of rehabilitation and dry weather period on improvement in surface condition. This was not examined in this paper.

CONCLUSION

The study analysed the impact of flooding on the surface conditions such as rutting and roughness of Queensland roads. Rapid increases in rutting values in flood affected sections, and in some cases, rapid increases in roughness were observed in this study. An extensive statistical analysis of flood affected Queensland roads shows significant increases in rutting and roughness following the flooding events. Flooding events in the last five years increased the cost of rehabilitation due to the increased deterioration of pavements. This study has demonstrated that there were significant correlations between pre-flood rutting values and increased road deterioration after floods. Pavements were categorized based on their pre-flood rutting values. A road with low pre-flood rutting is likely to have a lower increase in post flood rutting and roughness than a road with high pre-flood rutting (road in poor condition). The outcome of the study indicates that pre-flood rutting should be considered for modelling rapid deterioration of rutting of flood affected pavements.

A detailed assessment of the performance of flood affected roads is crucial for developing accurate and reliable deterioration models for these pavements. This study can be used to model the effects of rutting and roughness on rapid deterioration caused by the flooding. Although this paper did not include any model, this research is working on developing models for rapid deterioration of rutting and roughness. Future research should include building more resilient pavements in flood prone areas to minimise the impact of the post-flood rapid deterioration phase.

ACKNOWLEDGEMENT

The authors would like to thank Austroads and ARRB Group for providing the funding for the research. The award of the 2013 Austroads Fellowship for the Doctor of Philosophy study is greatly appreciated.

REFERENCES

Austroads (2007). "Guide to asset management: Part 5B: Roughness, by MA Moffatt, AGAM05B/07, Austroads Ltd.", Sydney, New South Wales, Australia.

Chen, X., and Zhang, Z. "Effects of Hurricanes Katrina and Rita Flooding on Louisiana Pavement Performance." *Geo-Shanghai 2014, May 26-28, Shanghai, China*, Pavement Materials, Structures, and Performance, ASCE GSP 239, 212-221.

Condric, I., and Stephenson, G. (2013). "Effect of December 2010 - January 2011 Storm & Flood Event on Brisbane City Council’s Road Network", *15th AAPA International Flexible Pavements Conference, "Delivering New Age Solutions",* Brisbane, Australia.

Foley, D. G. (1999). "Pavement condition monitoring in Australasia: the state of the art." *Research Report ARR331*, ARRB Transport Research Ltd., Australia.

Gaspard, K., Martinez, M., Zhang, Z., and Wu, Z. (2007). "Impact of Hurricane Katrina on Roadways in the New Orleans Area." *Technical Assistance Report No. 07-2TA*, LTRC Pavement Research Group, Louisiana Department of Transportation and Development, Louisiana Transportation Research Center, Louisiana.

Madanat, S., Nakat, Z., Farshidi, F., Sathaye, N., and Harvey, J. (2005). "Development of empirical-mechanistic pavement performance models using data from the Washington State PMS database", Research Report No. *UCPRC-RR-2005-05, USA*.

Meegoda, J. N., and Gao, S. (2014). "Roughness Progression Model for Asphalt Pavements Using Long-Term Pavement Performance Data." *Journal of Transportation Engineering*, 140(8), 1-7.

Paterson, W. D. O. (1987). "Road Deterioration and Maintenance effects; Models for Planning and Management." The Highway Design and Maintenance Standards Series, Baltimore and London: The Johns Hopkins University

Perera, R. W., and Kohn, S. D. (2001). "LTPP data analysis: Factors affecting pavement smoothness." *NCHRP Web Document 40, Michigan, USA*.

Salour, F., and Erlingsson, S. (2014). "Impact of groundwater level on the mechanical response of a flexible pavement structure, A case study at the Torpsbruk test section along county road 126 using a Falling Weight Deflectometer", Sweden.

Shahin, M. Y., Stock, C., and Beckberger, L. "Comparing pavement performance and its effect on maintenance and rehabilitation cost." *Third International Conference on Managing Pavement*, Transportation Research Board, 237–245.

SPSS Version 22.0. 2013. [Computer Software]. Armonk, NY: IBM Corp.

Sultana, M., Chai, G. W., Martin, T. C., and Chowdhury, S. H. (2014). "A Review of the Structural Performance of Flooded Pavements." *26th ARRB Conference – Research driving efficiency,* October 19-22, Sydney, New South Wales, Australia.

Sultana, M., Chai, G. W., Martin, T. C., and Chowdhury, S. H. (2015). “A Study on the Flood Affected Flexible Pavements in Australia”, *9th International Conference on Road and Airfield Pavement Technology,* August 9-13, Dalian, Liaoning, China.

Sultana, M., Chai, G. W., Martin, T. C., and Chowdhury, S. H. (2016). "Modelling the Postflood Short term Behavior of Flexible Pavements." *Journal of Transportation Engineering,* 04016042

TMR (2012). "Pavement Rehabilitation Manual." Deaprtment of Transport and Main Roads, Queensland, Australia.

TMR (2014). “Flooding and Road Pavements”, Transport and Main Roads, Queensland, Australia.

TMR (2015). “Transport and Main Roads, Queensland, Reconstruction Program.”

AUTHOR BIOGRAPHIES

Masuda Sultana

Masuda Sultana was the recipient of the 2013 Austroads Fellowship for PhD research to study the effects of flooding on pavements. She completed her Master of Philosophy (MPhil) degree in Engineering Management at Griffith University in 2012 and BSc in Civil Engineering from Bangladesh University of Engineering and Technology (BUET) in 2008. Masuda worked in the project management area for two years in Bangladesh after finishing the bachelor degree.

Dr Gary Chai

Dr Chai is the Principal Researcher of the Long-Term Pavement Performance (LTPP) study in South East Queensland. He is a Chartered Professional Engineer whose career on road pavement engineering spans nearly three decades in the USA, the Asia Pacific and in Australia.

Dr Chai has extensive experience in pavement design and management, highway construction and pavement engineering research. His areas of expertise include mechanistic analysis of pavement structures, soil mechanics of pavement foundation and the application of FWD testing for structural evaluation of pavement performance. His research interests include modelling of pavement deterioration, nonlinearity behaviour in pavement structures and Finite Element analysis of concrete pavements.

Dr Tim Martin

Dr Tim Martin is a Chief Scientist in road infrastructure management at ARRB. Before joining ARRB Group Ltd in 1990, Tim spent some 17 years in investigation, planning, design, contract management and economic evaluation of Australian and international engineering projects. Tim's research at ARRB Group has involved the design and implementation of observational studies using long term pavement performance (LTPP) sites, experimental studies with accelerated load testing, resulting in the development of a range of pavement deterioration and works effects models for a range of road types on sealed and unsealed pavements.

Dr Sanaul Chowdhury

Dr Chowdhury is the Project Manager for the Research Alliance on the Long-Term Pavement Performance study in South East Queensland. Dr Chowdhury is also an academic at Griffith University and has more than 25 years of extensive experience in reinforced and prestressed concrete structures, and road pavement design and construction, as well as in the teaching of related subjects both at undergraduate and postgraduate levels. He has research interests in the fields of strength and serviceability characteristics of reinforced and prestressed concrete structures, pavement design and management, and mechanical properties of high strength concrete.

Dr Yuri Anissimov

Dr Anissimov is Associate professor in Applied Mathematics at the School of Natural Sciences, Griffith University. Dr Anissimov has extensive experience in solving mathematical modelling problems in areas of engineering, bioengineering and pharmaceutical sciences.