



Deterioration of flood affected Queensland roads – An investigative study

Masuda Sultana^{a,*}, Gary Chai^b, Sanaul Chowdhury^b, Tim Martin^c

^a Griffith School of Engineering, Griffith University, QLD 4222, ARRB Group Ltd, Australia

^b Griffith School of Engineering, Griffith University, QLD 4222, Australia

^c ARRB Group Ltd, Melbourne, VIC 3133, Australia

Received 23 March 2016; received in revised form 4 October 2016; accepted 5 October 2016

Available online 14 October 2016

Abstract

The aim of this paper was to investigate the impact of recent flooding events on the structural and surface condition (such as roughness and rutting) of the pavements of the Department of Transport and Main Roads, Queensland, and the Brisbane City Council. The paper also reviewed the major flooding and cyclone events that occurred in the last six years in Queensland. Generally, a rapid increase in deterioration of the structural and surface conditions such as roughness and rutting was observed in pavements after the flood as a result of the inundation. An increasing need for road rehabilitation was also observed after the recent flooding events from 2010 to 2015 in Queensland. Assessing the rapid deterioration of the structural and surface condition of the flood affected pavements is a prerequisite for the accurate prediction of pavement performance, a better decision making process and the management of these roads. Although this paper did not include any model for roughness and rutting, deterioration models for roughness and rutting of flood affected pavements are currently being developed as a part of the future scope of this research.

© 2016 Chinese Society of Pavement Engineering. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Keywords: Pavement deterioration; Flooding; Structural and surface condition

1. Introduction

Australia has long had a history of extreme weather. These extremely variable climate events range from droughts to floods. Extreme weather events, such as intense heavy rainfall, tropical cyclones, flooding, hail storms, and heat waves are often short-lived, abrupt events lasting from several hours or up to several days. Such events are described as ‘shocks’ within the climate system; moreover they tend to be noticeably different from previous events

[1]. The flooding events have an impact on individuals and communities, as well as social, economic, and environmental consequences. The consequences of floods, both negative and positive, vary greatly, depending on the location and extent of flooding, and the vulnerability and value of the natural and constructed environments they affect [2]. Unpredictable calamities, such as the January 2011 flooding in South-East Queensland, Cyclone Olga in 2010, Cyclone Yasi in 2011, Cyclone Oswald in 2013 and Cyclone Marcia in 2015, affected the road infrastructure system across the area.

In total, Australia has a road network system of over 800,000 km (kilometres) and worth over AUS\$100 billion. Queensland has some 186,859 km of public roads. The stewardship of this network lies with two organizations, the Department of Transport and Main Roads, Queens-

* Corresponding author.

E-mail addresses: m.sultana@griffith.edu.au (M. Sultana), g.chai@griffith.edu.au (G. Chai), s.h.chowdhury@griffith.edu.au (S. Chowdhury), tim.martin@arrb.com.au (T. Martin).

Peer review under responsibility of Chinese Society of Pavement Engineering.

land (TMR) and the local government agencies. TMR manages approximately 33,344 km of State-controlled roads [3]. This road network is an important physical asset for the state and local governments.

The increasing frequency of extreme rainfall, cyclones and flooding events in recent years has significantly influenced the increasing rate of deterioration of the structural strength and surface conditions (such as roughness and rutting) of the pavements. The aim of this paper was to investigate the impact of recent flooding events on accelerating the deterioration of structural and surface condition such as roughness and rutting of flood affected pavements in Queensland. This paper also presents a review of literature on the recent flooding events and the adverse effects of recurrent occurrences of these events on the pavements of Queensland. The assessment of the rapid deterioration of the structural and surface conditions of flood affected pavements is a prerequisite for the accurate prediction of pavement performance, better decision making processes and management of these pavements. The study has a practical application in planning a systematic way of monitoring and managing flood affected pavements in future.

This study collected and analysed the surface condition data (roughness and rutting) of the flood affected pavements, of TMR, Queensland and the Falling Weight Deflectometer (FWD) deflection data of Brisbane City Council (BCC). The FWD test is the most widely used technique for non-destructive evaluation of pavements. During the FWD test, the pavement deflection response is measured by transducers at different offsets from the load. The maximum pavement displacements at transducer locations collectively referred to as the deflection bowl (or deflection basin) or the displacement time histories at each receiver location are then reported as pavement response. With pavement layer thicknesses as a given input, the measured pavement response is then analysed or back-calculated to infer the in situ pavement layer elastic moduli. The back-calculated pavement moduli are then used to design overlays, estimate remaining life of a pavement, identify weak areas in the pavement structure, or perform network level monitoring [4].

2. Literature review: Impact of recent flooding events

In Australia, Queensland experienced widespread and devastating flooding from December 2010 to January 2011 [2]. Tropical Cyclone Yasi, a Category 5 cyclone wreaked Northern Queensland in 2011. Some 59 rivers flooded, with 12 breaking flood records; approximately 19,000 km of state and local roads were affected by the 2010–2011 floods. It was estimated that the reconstruction and restoration of the flood affected areas would cost in the order of AUS\$5 billion, with damage sustained from Tropical Cyclone Yasi estimated to exceed AUS\$800 million [5]. Heavy rainfall also occurred over many parts of Queensland from 24 January to 8 February, 2010 associated with Tropical Cyclone Olga as the system weaved a path across

the state [6]. Many roads were flooded in the area of Yeppoon and Rockhampton on February 1, 2010.

Similarly, Brisbane City Council's 5600 km road network sustained inundation and extended high rainfall periods during the 2010 and 2011 summer wet season in Queensland. Brisbane experienced a significant river flood event of a scale not seen since the 1974 flood. Rainfall of between 600 to 1000 mm was recorded in most of the Brisbane River Catchment during December 2010 and January 2011 [7]. Two years after the flood, Brisbane City Council restored the city with work in excess of AUS\$400 million, including AUS\$127 million for roads and related infrastructure. Approximately 145,659 square metres of pavements were resurfaced by the council [8].

Tropical Cyclone Oswald tracked along the east coast of Australia from Mossman to Sydney from 22 to 29 January, 2013. Over, just four days, Gladstone (Queensland) received approximately 820 mm of rain. Major flooding devastated many areas in Queensland, extending from 22 January until 17 February, costing an estimated AUS\$2.4 billion [9]. The flooding events and associated heavy rainfall, a result of Tropical Cyclone Oswald, had a catastrophic effect on Queensland; for example, approximately 5845 km of State roads and 2800 km of State rail network were closed [10].

Following an unprecedented number of natural disasters between 2010 and 2013, extensive damage was caused to communities as well as key road, rail, port and waterway infrastructures. As a consequence, TMR reconstructed large sections of the state-controlled road network through the Transport Network Reconstruction Program (TNRP). These reconstruction works, costing approximately AUS\$6.4 billion, were completed on approximately 8741 km of the state-controlled road network, some 1733 structures (including bridges and culverts), some 1421 locations requiring earthworks and batters, and approximately 3335 locations needing silt and debris cleared [11].

In general, the procedures for the assessment of damage and deterioration of flood affected pavements are complex and time consuming [12]. One of the most important factors in analysing deterioration of flood-affected pavements is the existence of historical data and collection of data prior to, and after, the flood for the same road section [13]. A very crucial part in analysing these pavements is to compare the before and after scenario. To understand the deterioration of roads under flooding conditions, it is necessary to monitor flood affected pavements frequently and regularly (at least once a year or once every two years).

After the January 2011 flood, FWD testing was undertaken on flood affected roads of Brisbane City Council to identify the impact of flooding on the strength of the road network and its subsequent life. The selected roads included a range of known pavement types with different traffic loadings. The pavement types included granular pavement base with a thin Asphalt Concrete (AC) surface, deep strength asphalt pavement base and cement treated base (CTB) or cement stabilized pavements. The traffic

loadings ranged from local residential streets through industrial access roads to arterial roads [7].

The studies by Condric and Stephenson [7], Sultana, et al. [13], [14] and [12] presented the findings on the structural evaluation of the flood affected pavements in the Brisbane City Council area. Assessment of the impact of the January 2011 flooding on pavements in South-East Queensland by Sultana, et al. [12] and [13] indicated that within six to eight weeks of the flood, the structural strength of the pavements deteriorated more rapidly rather than gradually, as was originally predicted in their design. Comparison of the maximum FWD deflection (D_0) and the modified structural number of a flood affected road in Brisbane City Council area indicated that deflection values were higher after the flooding. Further, there was a decrease in the pavements' modified structural number (SNC) from 1.5% to 50% after the flood. The comparison of the FWD testing data collected in February 2011 (immediately after the flood) and in December 2014 (almost four years post-flood), indicated that as a result of the post-flooding rehabilitation work and subsequent dry weather period many pavement sections recovered their structural strength [12]. In the study, the structural capacity of the pavement was quantified using the modified structural number (SNC) [15]. The SNC is defined as the sum of the pavement structural number (SN) and the subgrade contribution (SN_{sg}). The subgrade contribution can be estimated from the Californian Bearing Ratio (CBR) of the subgrade [16]. The SNC values for the flexible pavements were calculated using Eq. (1) [17].

$$SNC = 3.2D_0^{-0.63} \tag{1}$$

where D_0 is the maximum deflection measured by a Falling Weight Deflectometer.

Although D_0 in Eq. (1) was originally measured by the Benkelman Beam (BB) deflections, the FWD and BB deflections were assumed to be the same in the study. Comparisons of the various means of estimating the SNC using either the maximum bowl deflection, D_0 , or a range of bowl deflections (D_0 , D_{900} and D_{1500}) suggest that the network level assessment of the SNC could be based on the D_0 deflection without any significant loss in accuracy. The bowl deflections other than D_0 , did not improve the

strength parameter estimation with the current strength and deflection relationships [18,19].

Sultana, et al. [12] developed a structural deterioration model (refers to Eq. (2)) that reflects the post-flood short term behaviour of a flexible pavement. The modified structural strength ratio, SNC_{ratiof} , is the dependent variable defining structural deterioration, while time is the independent variable.

$$SNC_{ratiof} = 1.032 - 0.034 \times EXP(t/21.5) \tag{2}$$

The model in Eq. (2) can be used to estimate modified structural number after flooding at each chainage if the initial, or before flooding, modified structural number is known.

Condric and Stephenson [7] indicated a significant reduction in pavement strength due to the ingress of water, which damaged and weakened supporting subgrade layers, after the January 2011 flooding. Visual inspections showed that extensive areas of surface and pavement failures occurred. The accelerated deterioration and loss of pavement life, due to the inundation and prolonged wet weather, were identified. Table 1 shows the streets with pre-flood FWD data and their remaining life span. The resultant asset damage by the flooding, and consequent loss of life on both new and older streets required significant early intervention [7].

The principal failure criteria considered to estimate remaining life was subgrade rutting using the design methodologies appropriate to the traffic loading level. Based on the traffic loadings, time to reach this loading was determined. For Heavily trafficked roads, the Department of Main Roads [20] tolerable deflection chart (refer to Fig. 1) was used to estimate remaining life in terms of Equivalent Standard Axles (ESAs). The overlay design chart for tolerable deflections follows Nomograph in Fig. 2 [7].

For Lightly trafficked roads, the tolerable deflection chart from Council's "Pavement Rehabilitation Design Manual" [21] was used to estimate remaining life (refer to Fig. 1). The loading in terms of ESA's was converted to years based on the traffic loading. The BCC Pavement Rehabilitation Design Guide [22] applied design tolerable deflection, $D_{tol} = 2.1$ mm for traffic loading up to

Table 1
Estimated lost life of streets with pre-existing FWD testing data [7].

Street/road	Suburb	Length (m)	AC depth (mm)	Pavement type	Traffic density (No. of ESAs)	Pavement age	Remaining life (years)		Lost life (years)
							Pre -Flood	Post -Flood	
Munro street	St. Lucia	151	25	Gravel	1.5×10^4	11	12.5	5.7	6.8
Luxford street	Chelmer	133	50	Gravel	3.7×10^4	36	2.6	0	2.6
Luxford street	Chelmer	133	50	Gravel	3.7×10^5	36	7.5	2.1	5.4
Park drive	Graceville	112	25	230 CTB	4.1×10^4	15	>40	32.8	8
Haig road	Milton	120	50	200 CTB	1.4×10^6	22	>40	>40	0
Haig road	Milton	179	50	200 CTB	1.4×10^6	22	>40	>40	0
Haig road	Milton	120	50	200 CTB	1.4×10^6	22	36	2	34
Haig road	Milton	179	50	200 CTB	1.4×10^6	22	>40	>40	0

ESA = Equivalent Standard Axle.

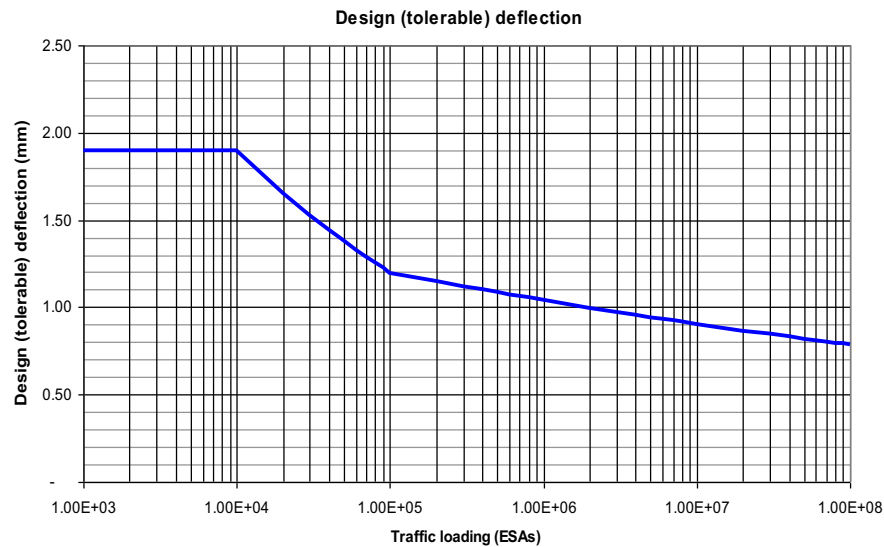


Fig. 1. Tolerable deflection on Council roads [24].

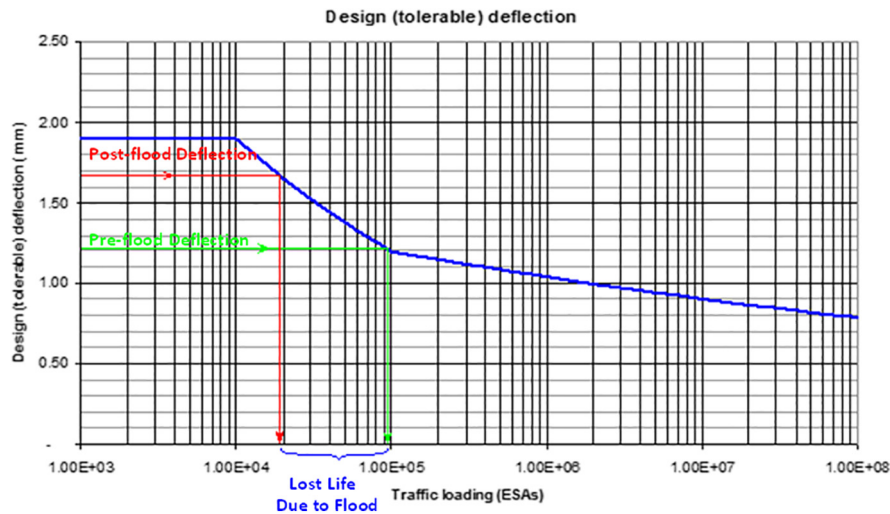


Fig. 2. Park Drive, Graceville – Effect of flooding on pavement life [12].

3.7×10^4 , and $D_{tol} = 1.6$ mm for traffic loading up to 1.5×10^5 . These values were derived from field investigation, and based on the assumption, that ‘a representative rebound deflection value is the mean of adjusted measured rebound deflections plus two standard deviation [21]. An example is shown in Fig. 2 where for Sherwood Road (Sherwood), Brisbane before the flooding, rutting of the subgrade did not control the life of the pavement. Whereas, post-flooding, rutting of the subgrade is estimated to occur in less than 4 years [7].

Prolonged inundation of roads can greatly impact upon the pavements. For example, the flooding, caused by Hurricane Katrina had a detrimental impact on the submerged pavement structures in New Orleans (USA) [23]. The results of this study showed that, the flood water did weaken AC pavement structures by reducing the stiffness of both the AC layer and subgrade in the New Orleans submerged area. Chen and Zhang [24] also identified an

increase in the damage to highways as a result of the heavy trucking or vehicle loading required for transporting the vast amounts of debris following Hurricanes Katrina and Rita (USA) in 2005. In addition, the study indicated that an escalation in deterioration occurred as subgrade components were not initially designed to sustain such vehicle loads. It may have been further weakened as the roadways were submerged in water for extended periods of time [24].

Therefore, review of literature also supports that it is imperative to investigate the loss of surface condition such as roughness and rutting of flood affected pavements in Queensland as there had been an increase in the extreme weather events, such as the flooding in recent years.

3. Methodology and data collection

This study assessed and investigated the surface condition in terms of roughness and rutting of some selected

flood affected pavements. Surface condition data were collected from TMR, Queensland. Roughness can develop from the loading of the pavement, and other factors, such as material volume changes associated with moisture changes. Rutting is a longitudinal deformation (depression) located in wheel paths; it is commonly found in flexible pavements. TMR, Queensland uses the International Roughness Index (IRI) to measure roughness [25]. The general methodology of data analysis is shown in Fig. 3. This study selected flood affected roads with both pre- and post-flood roughness and rutting data from TMR database. Statistical analysis using SPSS [26] was also undertaken to identify the overall condition of the road. It should be noted that not all the sections of the roads were similarly damaged or needed to be rehabilitated after the flood. A separate analysis of some highly deteriorated sections were also conducted.

Table 2 outlines possible distress limits for the deflection, roughness and rutting of pavements for their service life [18]. It was used as a general guideline to identify the highly deteriorated flood affected pavement sections.

The following two guidelines (refers to Eqs. (3) and (4)) were used to calculate the rate of increase or decrease in rutting and roughness values every year. The positive sign indicates an increase, and a negative sign indicates a decrease, in the rate of rutting or roughness value.

Rate of Rutting(mm/year)

$$= \frac{\text{Rutting at Year 2} - \text{Rutting at Year 1}}{\text{Year 2} - \text{Year 1}} \quad (3)$$

Rate of Roughness(IRI/year)

$$= \frac{\text{Roughness at Year 2} - \text{Roughness at Year 1}}{\text{Year 2} - \text{Year 1}} \quad (4)$$

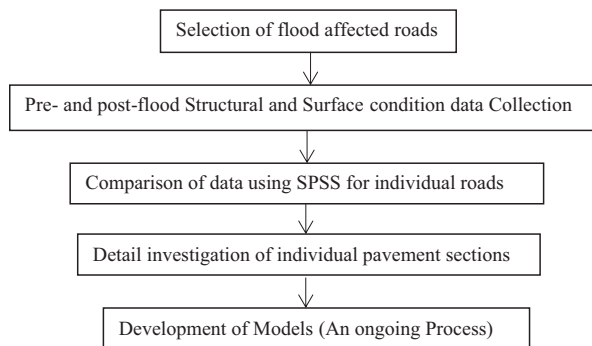


Fig. 3. Schematics of data collection and analysis.

CIRCLY5.0 [27] was used to calculate the layer moduli and subgrade CBR from the surface layer thickness of the pavement and FWD deflection data. The software was used as a tool to calculate the deflection values from the surface layer thickness, layer moduli and subgrade CBR. At first, the surface layer thickness and FWD deflection values for each testing location were recorded from the pavement history file. The layer moduli, CBR values, and surface layer thickness were used as the input parameters in the CIRCLY5.0. The trial and error method was used to estimate the layer moduli and CBR values until the deflection values from the CIRCLY 5.0 matched the field deflection values. The deflection values were finally obtained as an output from the CIRCLY5.0 which were similar to the field deflection values [28]. Some pavement section were also cross-checked by using EFROMD2 [29]. EFROMD2 was used to check if the results obtained from this software were closer to CIRCLY5.0. DCP (Dynamic Cone penetration) testing and four day soaked and unsoaked CBR testing were also conducted in 2015 on some test locations to check the field CBR values.

This methodology was adopted throughout this research to simplify the process of data collection and analysis. Excel spreadsheets, statistical software tool SPSS were used for the data analysis.

3.1. Rainfall data

The monthly rainfall data from the year 2009 to 2015 in Rockhampton and Ipswich were collected from the website of the Australian Bureau of Meteorology, for the purpose of the analysis (refer to Tables 3 and 4). The monthly rainfall was the total of all the available daily rainfall for the month. Observations of the daily rainfall were nominally made at 9 am local time and recorded the total for the previous 24 hours. The rainfall details included all forms of precipitation that reached the ground, such as rain, drizzle, hail and snow [30].

4. Analysis and discussion of results

Increases in surface condition distress were observed in many pavement sections following the January 2011 flooding. The photographs in Fig. 4 [32] indicate that deterioration of the surface condition were visible after the January 2011 flood in Munro Street, Brisbane [32]. The photographs in Fig. 5 indicate that there were rapid increases

Table 2
Definition of deflection, roughness and rutting limits for service life of pavement [18].

Road function	Surface deflection D_0 , (mm)	Roughness limit (IRI)	% Road length with rut depth > 20 mm
Freeways, etc.	0.8	4.2	10
Highways and main roads (100 km/h)	0.85	4.2	10
Highways and main roads (80 km/h)	0.9	5.4	20
Other sealed local roads	1.6	No defined limit	No defined limit

Table 3

Average monthly rainfall (mm) for Rockhampton area [30].

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2009	68.4	196.4	24	48.6	10.2	7.8	0.2	0.2	0	11.2	21.4	195.4	583.8
2010	62.8	256.2	142.6	4.2	18.6	16.4	16.2	65	147	50.6	120.6	523.8	1424
2011	114.4	65	315.4	41.8	19.4	23.4	9.2	94.4	0.4	61	5.2	152	901.6
2012	120.8	155	123.8	13.2	38.4	65.8	115	14	31.2	41	40.4	7.4	766
2013	555.6	109.6	207.4	99.2	121.4	7	18.2	0.6	5.8	26.2	59.8	2.8	1213.6
2014	178	225.2	247.8	69.2	11.6	6.2	0.8	34	85.6	2.8	13	154.2	1028.4
2015	150.2	281.8	3.4	49	19.2	40.4	13.4	10.8	1.6	8.8	60.4	39.2	678.2
2016	34	252.8	175	2.2	4.8	111.8	254.4						

Note: Station: Rockhampton Aero, Station Number: 039083, State: QLD, Opened: 1939, Status: Open.

Latitude: 23.38°S · Longitude: 150.48°E · Elevation: 10 m.

Table 4

Average monthly rainfall (mm) near Ipswich area [31].

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2009	66	84	31	185	254	68	2	5	30	30	112	82	949
2010	19	220	141	44	28	5	44	63	92	148	30	350	1184
2011	252	123	108	56	63	8	13	44	14	105	21	138	946
2012	168	76	59	72	8	78	42	2	7	18	94	24	648
2013	229	171	91	88	34	58	14	5	20	9	94	NA	
2014	NA	4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
2015	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	164	97	
2016	55	87	47	4	11	209	25						

Station name: One mile bridge alert (nearest station in the Ipswich area where rainfall data for the year 2009 to 2012 was available), Station Number: 040836 · State: QLD · Opened: 1990 · Status: Open · Latitude: 27.63°S · Longitude: 152.75°E · Elevation: 0 m. NA (Not available).



Fig. 4. Loss of surface condition after flood in Munro St, Brisbane (Photo Courtesy: BCC [32]).

in surface condition distress of Cordelia Street, South Brisbane following the same flood.

The rutting and roughness data from the year 2009 to 2014 of the 47 flood affected sections of the Rockhampton Emu Park Road in the Livingstone Shire Council, Central Queensland, have been plotted in Figs. 6 and 7. There were significant increases in rutting values in 45 pavement sections after the 2010 flooding event. Roughness values were also increased in a number of pavement sections of the Rockhampton Emu Park Road.

The rehabilitation work on the Rockhampton-Emu Park Road was completed in November 2011. As a result of the rehabilitation, the rutting and roughness data, collected from 2011 to 2014, shows significant improvement. However, very few sections again deteriorated in 2013 and 2014. The heavy rainfall event (nearly 300 millimetres of rain) in parts of the Capricorn Coast, from the morning of 25 March to 26 March, 2014, flooded around 50 roads in the Rockhampton, Livingstone and Gladstone Council areas [33]. The monthly rainfall data, (refer to Table 3) also



Fig. 5. Images shows deterioration of surface condition and pavement repair of flood affected parts of Cordelia Street, South Brisbane (pictures taken in 2015).

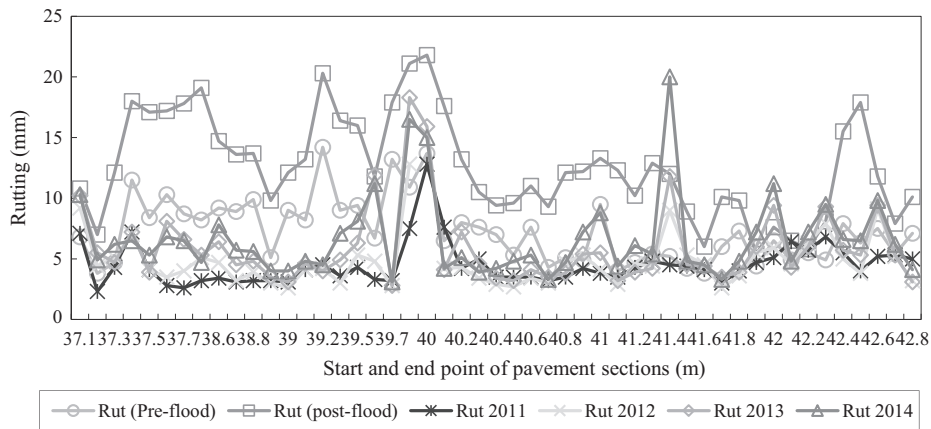


Fig. 6. Rutting plot for rehabilitated sections of Rockhampton – Emu Park Road, Livingstone Shire Council, Central Queensland.

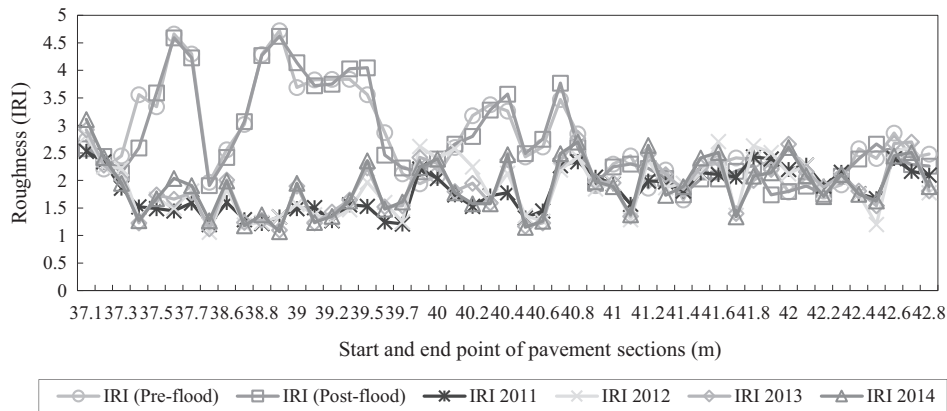


Fig. 7. Roughness plot for selected sections of Rockhampton-Emu Park Road, Livingstone Shire Council, Central Queensland.

confirm that there was heavy rainfall in the area in January and March 2013 and February and March 2014, which may be one of the possible causes of increasing rutting values in some sections of the road. Therefore, the deterioration of some sections could be initiated by the heavy rainfall and flooding events in 2013 and 2014. Three sections were identified as critical sections for the analysis: the data for roughness and rutting have been plotted in Figs. 8–10. The rate of increase and decrease in the rutting and roughness values of three critical sections is shown in Table 5.

The data for rutting and roughness from the year 2009 to 2014, for the selected flood affected sections (17 sections) of the Western Yeppoon-Emu Park Road in Livingstone Shire Council, Central Queensland have been plotted in Figs. 11 and 12. The rehabilitation works of these sections were completed in October 2011. There was an increase in the rutting values in 2010. Although, the rutting values in 2011, 2012 and 2013, shows some improvement, there was an increase in the roughness values in some sections in 2013 and 2014.

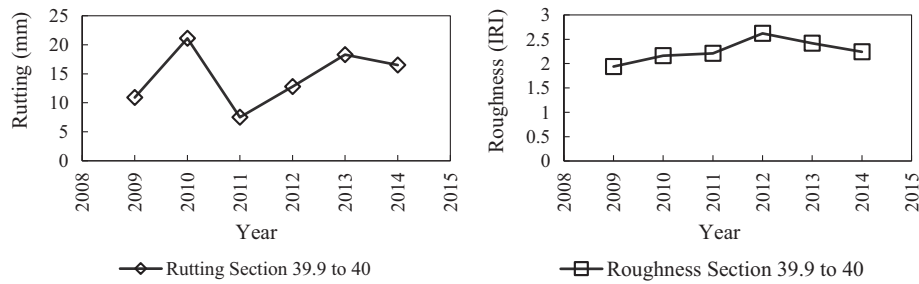


Fig. 8. Loss of Rutting and roughness in a section of Rockhampton-Emu Park Road, Livingstone Shire Council, Central Queensland.

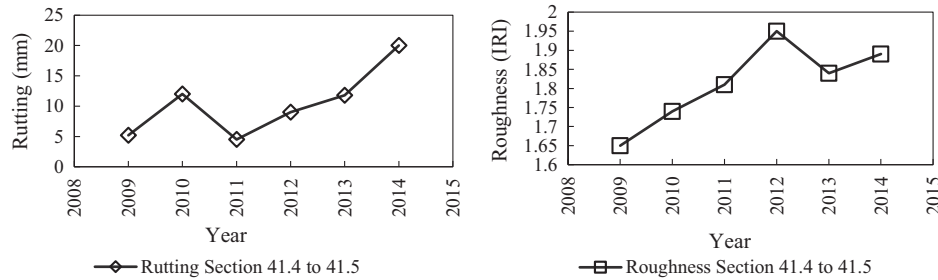


Fig. 9. Loss of Rutting and roughness in a section (Section ID 41.4 to 41.5) of Rockhampton-Emu Park Road, Livingstone Shire Council, Central Queensland.

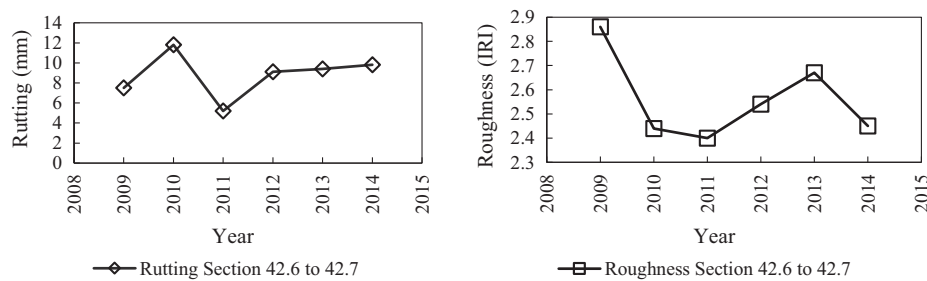


Fig. 10. Loss of Rutting and roughness in a section (Section ID 42.6 to 42.7) of Rockhampton-Emu Park Road, Livingstone Shire Council, Central Queensland.

Table 5

Rate of increase/decrease in rutting and roughness values every year of the three critical sections of Rockhampton-Emu Park Road.

ID	Increase/decrease in rutting (mm/year)					Increase/decrease in roughness (IRI/year)				
	2010	2011	2012	2013	2014	2010	2011	2012	2013	2014
Section 1 (39.9 to 40)	10.2	−13.6	5.3	5.5	1.8	0.22	0.5	0.41	−0.2	0.18
Section 2 (41.4 to 41.5)	6.8	−7.5	4.5	2.8	8.2	0.09	0.07	0.14	−0.11	0.05
Section 3 (42.6 to 42.7)	4.3	−6.6	3.9	0.3	0.5	−0.42	−0.04	0.14	0.13	−0.22

Note: Positive value means an increase and negative value means decrease in the rate of rutting and roughness values.

The data for the rutting and roughness for flood affected sections of the Rosewood-Marburg Road, Ipswich City Council have been plotted in Figs. 13 and 14. This road was flooded during the January 2011 flood. The rehabilitation of this road was completed in November 2012. While there were increases in the rutting values in 2011 and roughness values in 2011 and 2012, the rutting and roughness values decreased after the rehabilitation in 2012.

Table 6 shows mean rutting and roughness of three roads analysed in this study. Post-flood mean rutting of Rockhampton Emu Park Road, Western Yeppoon Emu Park Road and Rosewood Marburg Road were higher than pre-flood mean rutting. Post-flood mean roughness of Western Yeppoon Emu Park Road and Rosewood Marburg Road were higher than pre-flood mean roughness. Mean rutting in 2013 and 2014 of Rockhampton Emu Park

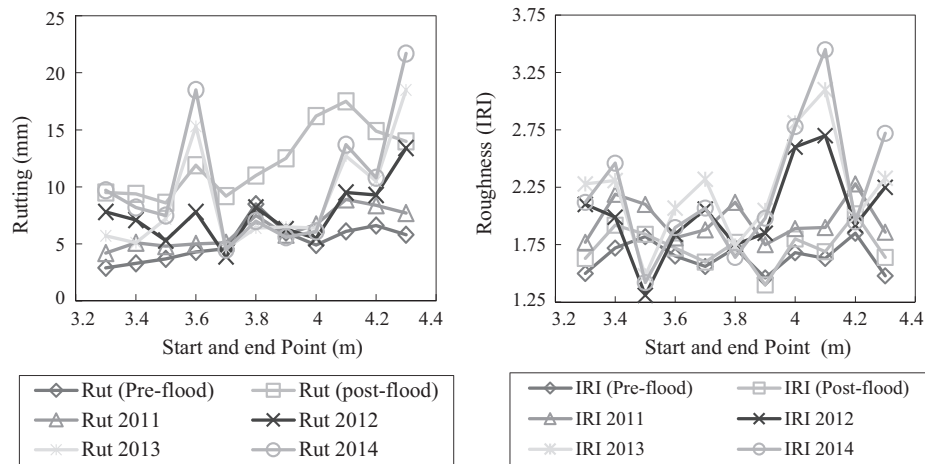


Fig. 11. Rutting and roughness plot for flood affected sections of Western Yeppoon-Emu Park Road, Livingstone Shire Council, Central Queensland.

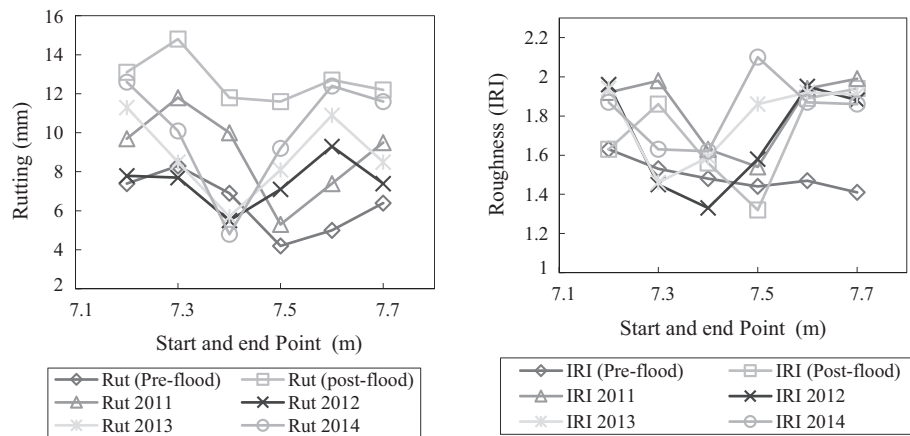


Fig. 12. Rutting and roughness plot for flood affected sections of Western Yeppoon-Emu Park Road, Livingstone Shire Council, Central Queensland.

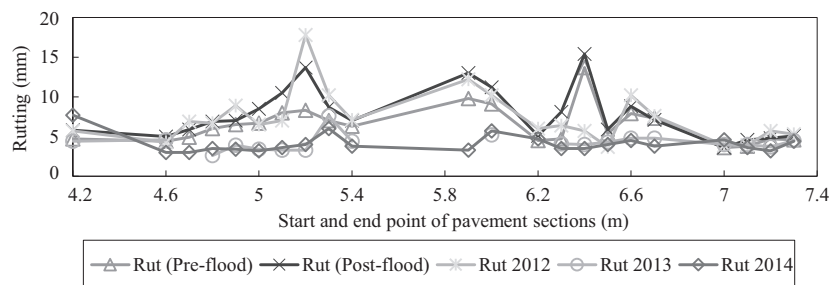


Fig. 13. Rutting plot for flood affected sections of Rosewood-Marburg Road in Ipswich City Council.

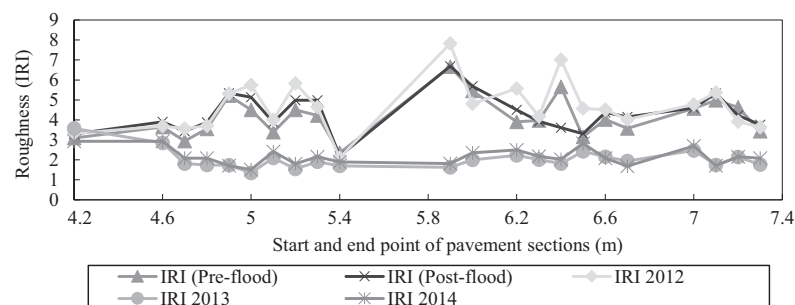


Fig. 14. Roughness plot for flood affected sections of Rosewood-Marburg Road in Ipswich City Council.

Table 6
Mean rutting and roughness.

Road Id	Road Name	Mean Rutting (mm)						Mean Roughness (IRI)						Rehabilitation Completed
		2009	2010	2011	2012	2013	2014	2009	2010	2011	2012	2013	2014	
194	Rockhampton Emu Park Road	7.3	12.6	4.5	4.8	5.9	6.7	2.77	2.73	1.81	1.89	1.90	1.90	03-Nov-11
197	Western Yeppoon Emu Park Road	5.6	12.4	7.2	7.6	8.9	10.2	1.59	1.72	1.91	1.91	2.07	2.08	12-Oct-11
303	Rosewood Marburg Road		6.5	7.8	7.4	4.3	4.1		4.15	4.33	4.64	2.03	2.16	21-Nov-12

Table 7
Thickness of surface layer (Luxford Street, Chelmer).

Section 1 (Ch. 0–65 m)	Section 2 (Ch. 65–133 m)
45–65 mm AC in original pavement (65–145 mm in patched area)	40–60 mm AC in original pavement
135–150 mm Gravel with sand & silt	190–200 mm Gravel with sand & clay
170 mm Clayey gravel with sand	
370–400 mm (Total thickness)	240–250 mm (Total thickness)

Road and Western Yeppoon Emu Park Road were increased again due to the heavy rainfall and flooding events in the area in 2013 and 2014. However, mean rutting in 2013 and 2014 of Rosewood Marburg Road improved after the rehabilitation completed in 2012.

The analyses of the different sections of the TMR roads indicate that the roughness and rutting values significantly increased following the floods of 2010, 2011 and 2013. As discussed previously, the before and after flood data are

important for assessment of flood affected pavements. However, due to lack of pre- and post-flood deflection data (from 2009 to 2014) of the same sections that had pre- and post-flood surface condition data, it was not possible to analyse structural and surface condition of the same flood affected pavement section. However, future studies can address the issue as many road agencies are now more frequently collecting data of flood affected pavements.

4.1. Luxford street in Chelmer, Brisbane – A case study

In Chelmer, Brisbane, Luxford Street was constructed in 1975. The thickness of the surface layers (tested on December 2010) is shown in Table 7. The subgrade is classified as Clay (with/without sand) in all sections and the moisture content is above the plastic limit that makes the pavement,

Table 8
Pavement condition data of Luxford street, Chelmer.

Inspection date	Pavement failures	Surface failures
7/12/2010	1.9%	2.1%
23/02/2011	2.3%	1.3%

Table 9
Calculation of layer moduli and CBR using CIRCLY5.0.

ID	Date	Thickness of AC layer (mm)	Thickness of granular layer (mm)	Asphalt modulus (MPa)	Granular layer modulus (MPa)	Subgrade CBR	D ₀	SNC
1R-12	8/12/2010	50	135	1500	150	14	0.89	3.44
	24/02/2011	50	135	1500	150	9	1.184	2.88
	9/12/2014	65	135	2000	200	14	0.721	3.93
1R-20	8/12/2010	140	145	2000	200	14	0.456	5.25
	24/02/2011	140	145	2000	200	9	0.599	4.42
	9/12/2014	140	145	2500	200	14	0.428	5.46
1R-28	8/12/2010	140	145	2500	200	14	0.428	5.46
	24/02/2010	140	145	2500	200	14	0.428	5.46
	9/12/2014	140	145	2300	200	10	0.522	4.82
2R-60	8/12/2010	140	260	2000	250	9	0.546	4.69
	24/02/2011	140	260	1800	250	3	1.1896	2.87
	9/12/2014	140	260	2000	250	3.5	1.074	3.06
2L-64	8/12/2010	130	260	2000	200	8.5	0.606	4.39
	24/02/2011	130	260	1500	200	4	1.047	3.11
	9/12/2014	140	260	2500	200	9	0.534	4.75

sensitive to the moisture. Further, Luxford Street is a relatively lightly trafficked residential street.

The street was one of the highly affected streets during the January 2011 flood. A visual inspection of surface condition was completed on the street after six weeks of the flood. Some areas of crocodile cracking without depression and extensive depressions over the storm water pipe were observed. Another inspection of the street on March 2011 indicated a small area of additional crocodile cracking which developed after the flood. The pavement condition data of this street are summarised in Table 8. A small increase (0.4%) in pavement failures was observed following the flood. Please note that not all sections of the road were highly deteriorated; some highly deteriorated sections were identified and analysed. The layer Moduli and CBR of some sections of the pavement were calculated using CIRCLY 5.0 and are shown in Table 9. The first column refers to the ID of the pavement section, first part of the ID refers to the wheelpath and second part refers to chainage (m). These pavement section were cross-checked by using EFROMD2 (Vuong 1992). Values obtained from CIRCLY 5.0 and EFROMD2 closely gives the similar results.

There was significant reduction in subgrade strength immediately after the flooding. The calculation of the layer modulus from CIRCLY5.0 indicates a decrease in strength in Asphalt and Granular layer in some sections. The sections were rehabilitated in 2011 to restore the subgrade strength. The deflection data indicated improvement in strength as a result of rehabilitation in 2011 and dry weather period in the area after the January 2011 flood.

5. Conclusion

The study's analysis of the flood affected sections of the Queensland roads showed that the roughness and rutting values had significantly increased following the heavy rainfall and flooding event from 2010 to 2014. Further, the flood-affected pavement sections had a rapid reduction in the structural and subgrade strength. The rapid reduction in structural and subgrade strength caused rapid deterioration of the surface condition, such as roughness and rutting. Pavements with weakened subgrade condition deteriorate rapidly when traffic starts to use the road again. Thus, a flooding event is directly related to the accelerated deterioration of the pavements as well as an increasing need for rehabilitation. The flood affected road sections investigated in the study needed rehabilitation to restore their strength. Therefore, flooding will continuously pose new difficulties for road agencies by increasing the cost of road maintenance.

The current study did not include analysis of the structural strength of TMR, Queensland pavement sections due to lack of deflection data before and after the recent flooding events. However, to enable this issue to be addressed by future research, the appropriate data should be collected following extreme weather events such as

heavy rainfall and flooding. Then, such data can be used to analyse and model the deterioration of flood affected roads over the long term. With the increasing occurrence of flooding events, future research should include modelling the rapid deterioration of surface conditions, such as roughness and rutting. As a part of this research project, deterioration models for rapid increase in rutting and roughness of flood affected roads are currently being developed by the researchers. A practical application of the current study is in the long term monitoring, planning and policy making of flood affected pavements and pavements in flood prone areas.

Acknowledgments

The authors would like to thank Austroads and the ARRB Group for funding the research. A special thanks to Dr. Greg Stephenson from Brisbane City Council for his substantial technical support in this research.

References

- [1] Climate Commission, The Critical Decade: Extreme Weather, 2013.
- [2] Chief Scientist, Understanding floods: questions and answers, Australian Journal of Emergency Management and Office of the Queensland Chief Scientist, vol. 26, 2011.
- [3] TMR. The State Road Network of Queensland Online. Available: <<https://data.qld.gov.au/dataset/state-controlled-road-length-total-kilometers/resource/17a795fc-fdf6-4220-969d-22ba6fdc1d54>>, <http://www.google.com.au/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=0CCYQFjAB&url=http%3A%2F%2Fwww.tmr.qld.gov.au%2F-%2Fmedia%2FTravelandtransport%2FMaps%2520and%2520guides%2FQueensland%2520maps%2FState%2520road%2520network%2Fsrnbackcover.pdf&ei=PIVZVMr-JKegmQWBsYCACA&usq=AFQjCNGeG-MIzrDHHO-KEQC-6f4N9bI2EhA&sig2=z-oBUEV46JLwppXLO_0ibA&bvm=bv.78677474,d.dGY>.
- [4] R. Hadidi, N. Gucunski, Comparative study of static and dynamic falling weight deflectometer back-calculations using probabilistic approach, *J. Transp. Eng.* 136 (2010) 196–204.
- [5] Queensland Reconstruction Authority, Operation Queensland The State Community, Economic and Environmental Recovery and Reconstruction Plan 2011–2013, 2013.
- [6] BoM, Floods associated with Tropical Cyclone OLGA January and February 2010, 2010.
- [7] I. Condric, G. Stephenson, Effect of December 2010–January 2011 storm & flood event on Brisbane City Council's Road Network, in: Presented at the 15th AAPA International Flexible Pavements Conference, Delivering New Age Solutions, Brisbane, Australia, 2013.
- [8] BCC, Fact Sheet Brisbane City Council Two year Flood Recovery Update, January, Brisbane City Council, 2013.
- [9] BoM, Monthly weather review January 2013, 2013.
- [10] Queensland Government, Queensland 2013 Flood Recovery Plan (for the events of January–February 2013), 2013.
- [11] TMR. Transport and Main Roads, Queensland, Reconstruction Program [Online]. Available: <<http://www.tmr.qld.gov.au/Projects/Featured-projects/Reconstruction-program.aspx>>, (accessed 5.11.2015).
- [12] M. Sultana, G.W. Chai, T.C. Martin, S.H. Chowdhury, Modelling the postflood short term behavior of flexible pavements, *J. Transp. Eng.* 142 (2016).
- [13] M. Sultana, G.W. Chai, T.C. Martin, S.H. Chowdhury, A review of the structural performance of flooded pavements, in: Presented at the

- 26th ARRB Conference – Research driving efficiency, Sydney, New South Wales, 2014.
- [14] M. Sultana, G. W. Chai, S.H. Chowdhury, T.C. Martin, Rapid deterioration of pavements due to flooding events in Australia, in: Presented at the Fourth Geo-China International Conference, Geo-China 2016: Innovative and Sustainable Solutions in Asphalt Pavements, Shandong, China 2016.
- [15] T. Watanatada, C.G. Harral, W.D. Paterson, A.M. Dhareshwar, A. Bhandari, K. Tsunokawa, The highway design and maintenance standards model, Volume 1. Description of the HDM-III Model, A World Bank Publication, The Johns Hopkins University Press, Washington, D.C., 1987.
- [16] J.W. Hodges, J. Rolt, T.E. Jones, The Kenya road transport cost study: research on road deterioration, TRRL laboratory report 673. Crowthorne, Berkshire, UK, 1975.
- [17] W.D.O. Paterson, Road deterioration and maintenance effects; models for planning and management, The Highway Design and Maintenance Standards Series, The Johns Hopkins University, Baltimore and London, 1987.
- [18] Austroads, Pavement Strength in Network Analysis of Sealed Granular Roads: Basis for Austroads Guidelines, AP-R233, Sydney, NSW, Australia 2003.
- [19] T.C. Martin, S. Crank, Use of Pavement Strength Information in Network Asset Management, ARRB Transport Research Contract Report RC1702, Austroads Project No. BS.A.C.025, October 2001, pp 32, Vermont South, Victoria, 2001.
- [20] Department of Main Roads, Methodology for Designing Pavement Rehabilitation Treatments, Report no. DG9228/7000, April 2007, 2007.
- [21] BCC, Pavement Rehabilitation Design Manual, Brisbane City Council, 2011.
- [22] BCC, Pavement Rehabilitation Design Manual, Brisbane City Council, 1993.
- [23] Z. Zhang, Z. Wu, M. Martinez, G. Kevin, Pavement structures damage caused by Hurricane Katrina flooding, *J. Geotech. Geoenviron. Eng.* 134 (2008) 633–643.
- [24] X. Chen, Z. Zhang, Effects of Hurricanes Katrina and Rita Flooding on Louisiana Pavement Performance, in *Geo-Shanghai 2014*, May 26–28, Shanghai, China, 2014.
- [25] TMR, 2012. Pavement Rehabilitation Manual. Available: <<http://www.tmr.qld.gov.au/business-industry/Technical-standards-publications/Pavement-Rehabilitation-Manual.aspx>>.
- [26] SPSS Version 22.0, [Computer Software]. Armonk, NY: IBM Corp. ed, 2013.
- [27] L. Wardle, CIRCLY software program for the mechanistic analysis and design of road pavements, Mincad Systems, Australia, 2009.
- [28] M. Sultana, G.W. Chai, T.C. Martin, S.H. Chowdhury, A study on the flood affected flexible pavements in Australia in: Presented at the 9th International Conference on Road and Airfield Pavement Technology, Dalian, Liaoning, China, 2015.
- [29] B. Vuong, A computer-based program for back-calculating elastic material properties from pavement deflection bowls, in: Victoria (Ed.), Australian Road Research Board Ltd, Australia, 1992.
- [30] BoM. Climate data online monthly rainfall, Australian Bureau of Meteorology [Online]. Available: <http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=139&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=040913>.
- [31] BoM. Monthly rainfall Rockhampton Aero, Australian Bureau of Meteorology [Online]. Available: <http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=139&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=039083>, (accessed February 2016).
- [32] BCC, Brisbane City Council, ed, 2012.
- [33] W. Rollo, P. Robinson, Downpour in central Qld floods dozens of roads with more rain to come, ed, 2014.