A REVIEW OF THE STRUCTURAL PERFORMANCE OF FLOODED PAVEMENTS

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ABSTRACT

This paper presents the effects of flood on the structural performance of pavements. Severe floods occurred in 2010 and 2011 in Southeast Queensland which prompted a need to monitor road pavements subject to frequent flooding. The long-term observation of pavements subject to flooding can provide answers as to why some roads largely survive flooding but others can be greatly impacted by flooding. A study conducted by ARRB Group and Griffith University, with Austroads funding, commenced in early 2013 to quantify the impacts of flooding on pavement deterioration. The study examines the structural and functional performance of flooded pavements using the Falling Weight Deflectometer (FWD) and surface condition data sourced from Brisbane City Council, the Department of Transport and Main Roads Queensland, and Roads and Maritime Services of New South Wales.

The FWD deflection and surface condition data collected prior to and after the flooding events were used in modelling pavement deterioration. The deflection data was analysed using the CIRCLY5 program to back-calculate the stiffness moduli of the various pavement layers including the subgrade CBR. With the stiffness modulus, the Structural Numbers of pavement sections could be calculated.

The preliminary results obtained from several road sections indicate a consistent trend with increased FWD deflection and reduced structural strength immediately after the flood events, as expected. However, strength gains were observed in a number of pavement sections several months after flooding mainly due to post-flooding rehabilitation work. A literature review of pavement deterioration under extreme climatic conditions of flooding in other regions of the world is also presented. The study is expected to provide valuable information regarding building resilience into future road pavements and predicting the cost consequences for when this resilience cannot be built-in.

INTRODUCTION

Flooding is recognised globally as an issue of utmost concern and the threat of flooding poses problems to all nations. In 2010, La Niña was exceptionally strong in Australia, as measured by the Southern Oscillation Index. The months of August to December of 2010 were very wet with the heavy rains in earlier months extending south to include most of Victoria and Tasmania. The most widespread and damaging floods occurred across Queensland in the final week of 2010 and continued into early 2011. The most severe impacts were in central and southern inland Queensland. Numerous rivers throughout the region reached record levels (BoM 2010). From December 2010 to January 2011, Queensland experienced widespread flooding, with three-quarters of the state declared a disaster zone (Chief Scientist 2011). Significant flooding also occurred across inland New South Wales in December, particularly in the Murrumbidgee and Lachlan catchments (BoM 2010).

Recent flood and cyclone events raise new challenges in efficiently maintaining road pavements. The Chief Executive of the Local Government Association of Queensland (Mr Greg Hallam) mentioned that the largest effect would be on the state’s roads, with between
70,000 km to 90,000 km of council roads damaged by floods. Restoring the state's infrastructure would take a couple of years because some had been completely wiped out (Brisbane Times 2011). Moreover, in 2013, the effects of ex-tropical cyclone Oswald also damaged Queensland roads. With the evidence regarding the increased frequency of extreme rainfall events, it is expected that over the next few years, pavements will be subject to more extreme climatic conditions over their design life than was originally anticipated. As a result, extreme weather will continue to pose challenges to state and local government authorities.

The flood events which occurred in 2010-2011 in South-East Queensland raised the importance of monitoring road pavements subject to frequent flooding. It is therefore imperative to have an in-depth understanding of the structural performance of pavements under flooding conditions. Long-term observation of pavements is also instrumental in providing answers to why some roads survived flooding but others were highly impacted by the events. This issue will be addressed in this paper.

**AIM OF THE RESEARCH**

This study commenced in early 2013 and has been funded by Austroads and the ARRB Group in a collaborative research arrangement between ARRB and Griffith University. The initial stage of the project involved the collection of pavement condition data (structural and surface conditions) on flood-affected roads managed by Brisbane City Council (BCC), the Department of Transport and Main Roads Queensland (TMR) and Roads and Maritime Services, New South Wales (RMS NSW). The study aims to understand the impacts of flooding on pavement deterioration by examining the structural performance of flooded pavements using Falling Weight Deflectometer (FWD) deflection and surface condition data sourced from BCC, TMR and RMS.

The deflection data was analysed using the CIRCLY5 program (Wardle 2009) to back-calculate the stiffness moduli of the various pavement layers including the California Bearing Ratio (CBR) of the subgrade. With stiffness modulus, the structural numbers of pavement sections can then be calculated. Although this paper focuses only on the structural deterioration of pavements, other surface conditions are also being monitored.

**LITERATURE REVIEW**

Monitoring and modelling pavement performance subject to flooding is not a simple task. Unlike the conventional approach of modelling pavement deterioration under normal climatic conditions, flooded pavements introduce a new dimension into the already complex mathematical model when pavements are either partially or fully saturated. These dynamic conditions add new challenges for road engineers managing road assets. As well as being capable of withstanding the expected traffic load, the design of pavements is based on moisture and temperature patterns reflecting the historical climate of the location.

The factors that affect the deterioration of pavement can be categorised as follows after Ramaswamy and Ben-Akiva (1990):

- pavement characteristics: pavement strength, layer thicknesses, base type, surface type
- pavement history: time since last rehabilitation, total pavement age
- traffic characteristics: average daily traffic, cumulative traffic, traffic mix (percentage of trucks)
- environmental variables: average monthly precipitation, number of freeze-thaw cycles and average annual minimum temperature.
In the United States (US) in 2005 two devastating hurricanes, Katrina and Rita, hit the states of New Orleans and the south-eastern and south-western portion of Louisiana. Approximately 3,220 km of roadway in the Greater New Orleans area were submerged by floodwaters for up to five weeks. Immediately after the hurricanes, there was great concern in the state about the integrity of pavement structures in the flooded area due to the sustained flooding (Zhang et al. 2008). As such, the pavements, although appearing unaffected, may have suffered from undetected damage in the roadbed soils that could result in failures at a later time when emergency federal funds are no longer available (Helali et al. 2008).

Louisiana Transportation Research Centre (LTRC) sent investigative teams to assess the flooding impact on pavement structures in the area. This pilot study included collection of FWD surface deflection data and the use of this data to back-calculate the elastic moduli of the pavement layers. Another deflection measuring device, the Dynaflect, was used to determine the structural number (SN) and subgrade resilient modulus of the tested pavements. Coring at different locations was also carried out to verify the in situ pavement thickness and the integrity of pavement structure (Zhang et al. 2008).

Another study was performed to assess the extent of damage to Jefferson Parish’s (JP) road pavements caused by hurricanes Katrina and Rita. The study involved selecting a study area with a total road length of 338 miles, which represents approximately 20% of the JP road network, using an approach that involved; estimating the pre-Katrina/Rita pavement conditions; evaluating the post-Katrina/Rita pavement conditions; and, analysing the pavement damage. The pavement damage analysis involved before-and-after roughness, surface distress and structural analyses, as well as statistical analyses (e.g. ANOVA) to test the extent and significance of the damage (Helali et al. 2008). The roadway level analysis showed that on the roadways that were partially flooded, the flooded sections had higher deflection values (weakened structural condition) than the sections that were not flooded, indicating damage due to flooding. As an example, Figure 1 shows the entire roadway was historically (pre-Katrina) structurally homogeneous, however; post-Katrina data shows that the flooded sections seem to have higher deflection values, indicating damage from the flooding (Helali et al. 2008).

ARRB initiated a study in 2000 to develop both sealed and unsealed mechanistic-empirical (ME) deterministic road deterioration (RD) models suitable for Australian local road conditions. Development of the structural deterioration model was based on a non-linear form involving the pavement age, expected design life (DL), climate and traffic independent variables. It was found that Equation (1) for the strength ratio, $S_{NC}$, the dependent variable defining structural deterioration, was the most appropriate for the selected data set (Martin et al. 2011).
\[ SNC_{\text{ratio}} = k_s \times 0.919 \times \left[ 2 - \exp \left( 0.242 \times \frac{\text{AGE}_i}{\text{DL}} + 0.507 \times \text{MESA} \right) \right] \]  

(1)

Where:

- \( SNC_{\text{ratio}} \) = \( SNC_i / SNC_o \)
- \( SNC_i \) = modified structural number of the pavement/subgrade strength at time of pavement age, \( \text{AGE}_i \)
- \( D_{oi} \) = maximum deflection measured at pavement age, \( \text{AGE}_i \), using a Falling Weight Deflectometer (FWD) or Heavy Weight Deflectometer (HWD)
- \( SNC_o \) = initial modified structural number of the pavement/subgrade strength at pavement age, \( \text{AGE}_i = 0 \) (estimated recursively using equation (1))
- \( k_s \) = local calibration factor for structural effects (default = 1.0)
- \( \text{EXP} \) = exponential function
- \( \text{AGE}_i \) = pavement age, the lesser of the number of years ‘i’ since construction or last rehabilitation
- \( \text{DL} \) = expected (assumed) design life of the pavement (years).

**STUDY DATA COLLECTION**

The road type considered for this study is sealed local roads. After reviewing the literature, the factors that were considered during the sampling and collection of data are as follows:

- any rehabilitation works conducted just before the flooding occurred (BCC 2012)
- the availability of data for the same road pavement section before and after 2011 and 2013 floods (BCC 2012; RMS 2013)
- pavement history data: pavement age (BCC 2012; RMS 2013)
- pavement profile data: traffic density and thickness of the surfacing layer (BCC 2012)
- traffic classification data (BCC 2012)
- deflection data from FWD testing (BCC 2012; RMS 2013)
- visible surface condition deterioration such as rutting, roughness, cracking and potholing data (RMS 2013).

The most important factors for assessing the deterioration of flood-affected roads are historical data for the before and after analysis; pavement profile: traffic density; thickness of the surfacing layer; traffic classification and any visible surface condition deterioration. This study aims to assemble all available FWD deflection and surface condition data of flood-affected roads across Australia. FWD deflection data before and after floods will be used to evaluate the reduction of structural strength. These data will be used to develop a deterioration model for the impact of gradual rise of river water. Data is being collected using mainly two sources highlighted as follows:

- participating organisations: data collected from BCC, TMR, and RMS NSW
- published database: climatic condition or flood level data will be collected from published sources.

The BCC has provided FWD data collected along the flood-affected roads. They have a record of historical data in their pavement management system (PMS) which included deflection data from FWD testing for different chainages and each lane, traffic classification and surfacing layer thickness data. They have provided data for 16 flood-affected road sections. Among them only two road sections have both before and after flood deflection data. They have decided to monitor some roads regularly after the January 2011 flood event. No record of surface condition data has been found for the flooded pavements from BCC. A list of roads that were partially or fully flooded during January 2011 can be found on the council website (see Table 1) (BCC 2012).
Table 1: Post-January 2011 flood - road strength investigation

<table>
<thead>
<tr>
<th>Suburb</th>
<th>Street</th>
<th>Length (m)</th>
<th>Extent of Inundation</th>
<th>FWD Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auchenflower</td>
<td>Haig Road</td>
<td>400</td>
<td>Partial</td>
<td>5/04/2011</td>
</tr>
<tr>
<td>Chelmer</td>
<td>Longman Terrace</td>
<td>212</td>
<td>Partial</td>
<td>25/02/2011</td>
</tr>
<tr>
<td>Chelmer</td>
<td>Loxford Street</td>
<td>133</td>
<td>Total</td>
<td>24/02/2011</td>
</tr>
<tr>
<td>Chelmer</td>
<td>Regatta Street</td>
<td>74</td>
<td>Partial</td>
<td>24/02/2011</td>
</tr>
<tr>
<td>Chelmer</td>
<td>Sutton Street</td>
<td>276</td>
<td>Partial</td>
<td>28/02/2011</td>
</tr>
<tr>
<td>Corinda</td>
<td>Denmen Street</td>
<td>541</td>
<td>Partial</td>
<td>11/04/2011</td>
</tr>
<tr>
<td>Gracemere</td>
<td>Park Drive</td>
<td>227</td>
<td>Partial</td>
<td>11/04/2011</td>
</tr>
<tr>
<td>Jindalee</td>
<td>Sinnamon Road</td>
<td>747</td>
<td>Partial</td>
<td>11/04/2011</td>
</tr>
<tr>
<td>Milton</td>
<td>Haig Road</td>
<td>299</td>
<td>Total</td>
<td>5/04/2011</td>
</tr>
<tr>
<td>Mount Ommaney</td>
<td>Westlake Drive</td>
<td>1121</td>
<td>Partial</td>
<td>13/04/2011</td>
</tr>
<tr>
<td>Oxley</td>
<td>Aldersgate Street</td>
<td>380</td>
<td>Partial</td>
<td>13/04/2011</td>
</tr>
<tr>
<td>Rocklea</td>
<td>Franklin Street</td>
<td>337</td>
<td>Total</td>
<td>1/03/2011</td>
</tr>
<tr>
<td>Rocklea</td>
<td>Grindle Road</td>
<td>616</td>
<td>Total</td>
<td>5/04/2011</td>
</tr>
<tr>
<td>Rocklea</td>
<td>Sherwood Road</td>
<td>1979</td>
<td>Total</td>
<td>20/02/2011</td>
</tr>
<tr>
<td>Sherwood</td>
<td>Sherwood Road</td>
<td>1017</td>
<td>Partial</td>
<td>12/04/2011</td>
</tr>
<tr>
<td>South Brisbane</td>
<td>Cordelia Street</td>
<td>881</td>
<td>Partial</td>
<td>1/03/2011</td>
</tr>
<tr>
<td>St Lucia</td>
<td>Munro Street</td>
<td>609</td>
<td>Total</td>
<td>19/04/2011</td>
</tr>
<tr>
<td>Westlake</td>
<td>Westlake Drive</td>
<td>275</td>
<td>Partial</td>
<td>13/04/2011</td>
</tr>
</tbody>
</table>

Approximately 310 km of BCC’s road network was inundated due to flooding in January 2011. Table 2 shows the total network area as well as the approximate pavement area inundated for each traffic classification of roads in Brisbane. Overall, 4.9% of the pavements by road length were inundated during the flood. The highest percentages of inundated pavements were for arterial ‘G’ roads (17.2%) and industrial access ‘E’ roads (13%) (BCC 2012).

Table 2: The total network area and approximate pavement area inundated for each traffic classification of roads in Brisbane

<table>
<thead>
<tr>
<th>Traffic Class</th>
<th>Total Network Area (m²)</th>
<th>Approx. Flooded Area (m²)</th>
<th>% Flooded Roads in Traffic Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4,691,896</td>
<td>110,478</td>
<td>2.4%</td>
</tr>
<tr>
<td>B</td>
<td>29,103,363</td>
<td>934,209</td>
<td>3.2%</td>
</tr>
<tr>
<td>C</td>
<td>6,191,256</td>
<td>258,009</td>
<td>4.2%</td>
</tr>
<tr>
<td>D</td>
<td>6,243,718</td>
<td>286,780</td>
<td>4.6%</td>
</tr>
<tr>
<td>E</td>
<td>3,538,454</td>
<td>459,640</td>
<td>13.0%</td>
</tr>
<tr>
<td>F</td>
<td>1,480,970</td>
<td>105,236</td>
<td>7.1%</td>
</tr>
<tr>
<td>G</td>
<td>2,695,503</td>
<td>464,939</td>
<td>17.2%</td>
</tr>
<tr>
<td>N</td>
<td>65,489</td>
<td>3,124</td>
<td>4.8%</td>
</tr>
<tr>
<td>Total</td>
<td>54,010,649</td>
<td>2,622,415</td>
<td>4.9%</td>
</tr>
</tbody>
</table>

RMS NSW provided a list of inundated sites. Their data included information such as pre-and post-flood deflection data; pavement type; pavement category; surface width; construction year; carriageway type and year of last rehabilitation or resurfacing. They did not have a record of surfacing layer thickness in their PMS. Austroads (2010) guideline will be used to calculate the subgrade CBR and structural number (SN). RMS NSW has also provided surface condition data which includes measurements of roughness, rutting and cracking.
TMR was able to provide a list of road sections where a flood recovery project occurred. This subset of data covered approximately 1,700 km of road length. This data set includes pavement age, type, depth, sealed or unsealed, type, seal age, seal life and seal width, average annual daily traffic (AADT), percentage heavy vehicle traffic, roughness, rutting, sealed pavement age, road class, unsealed pavement age, roughness, ride and rutting quality class.

**METHODOLOGY**

The FWD deflection and surface condition data collected prior to and after the flooding events were used in modelling pavement deterioration. This modelling was done using the deflection data to obtain the stiffness moduli of the various pavement layers by back-analysis with the CIRCLY 5.0 program to establish the subgrade CBR and calculate the structural numbers (SN) of pavement sections. The preliminary results obtained from several road sections indicated a consistent trend of increased FWD deflection and reduced structural strength immediately after the flood events. However, strength gains were observed in a number of pavement sections several months after flooding due to rehabilitation work.

Pavements subject to flooding are expected to experience rapid deterioration immediately after flooding. Two streets (Luxford Street in Chelmer and Haig Road in Milton, Brisbane) have both before and after FWD deflection data. Initially, deflection data of Luxford Street in Chelmer was back-calculated using CIRCLY 5.0. The modulus of the surfacing asphalt and granular base layer and subgrade CBR were calculated from this procedure. Austroads (2010) recommended the equation (2) to compute modified structural number (SNC) from FWD maximum deflection, $D_0$, as follows:

$$SNC_i = 3.2 \times D_0^{-0.63}$$  \hspace{1cm} (2)

Where:

- $SNC_i$: modified structural number at age ‘i’ (Paterson 1987)
- $D_0$: maximum deflection (mm) at load centre at age ‘i’.

The flow diagram in Figure 2 represents the arrangement and organisation of data for analysis purposes. Analyses were conducted using Excel worksheets and the statistical software tool, SPSS.

![Flow diagram for the arrangement and organisation of data.](image)

**ANALYSIS AND RESULTS**

If flooding has any effect on pavement, the affected sections should have a higher deflection, a lower structural number or modified structural number (SN or SNC), and lower subgrade resilient modulus than prior to flooding. Figure 3 shows the FWD maximum deflection data versus chainage and the back-calculated structural number versus chainage graph of four lanes of Luxford Street, Chelmer in Brisbane. These graphical representations clearly illustrate that
Deflection values are higher after flooding. They also indicate that there is a decrease in the pavement’s SN value after flooding. These graphs indicate that structural strength of the pavement section reduces significantly after flood. The reduction of structural numbers in different pavement sections ranges from 1.5% to 50%. It indicates the need for further investigation of the data to quantify the reductions. It includes analysing deflection data at chainages where major changes in deflection and structural number occurred after flood.

*Figure 3a: Maximum deflection versus chainage and structural number versus chainage in Luxford St. in Chelmer.*
The flood reached its peak on 13 January, 2011 in Brisbane and FWD deflection testing of Luxford Street was undertaken on 24 February 2011. Analysis indicates that many chainages along Luxford Street have lost a significant amount of their subgrade strength within this six week time period. These chainages were selected again and analysed using CIRCLY 5.0 to assess the trend in the change of deflection and structural number (see Figure 4) with the elapse of time.

Figure 4 shows that deflection values have significantly increased and Structural numbers have decreased greatly within a relatively short period (six weeks). At chainage 12 m, the maximum deflection value increased from 0.9 to 1.2 mm and the structural number decreased from 3.45 to 2.85. The reductions in SN values would not be so high if the road were to deteriorate under normal weather conditions without the flooding event. The reduction in structural number ranges from 11% to 29% at different chainages. The decrease in the pavement strength after the flood could lead to a reduction in the service life of the pavement sections if no measures were undertaken to rehabilitate or repair it.
CONCLUSION

The preliminary findings indicate that the reduction of strength of the road pavements due to floods range from 1.5% to 50.0%. The changes occurred within a relatively short period of time (approximately six weeks). These results indicate that the strength of inundated pavement sections is significantly impacted by the flood. Although, the principal objective of this research project is to develop a deterioration model to predict structural deterioration of flood-affected roads, the deterioration of functional conditions, such as roughness, cracking and rutting, will be included in next phase of the study.

It is envisaged that the outcomes of the research will provide quantifiable engineering knowledge for state and local road authorities in managing flooded road pavements. The study is also expected to provide valuable information regarding what is needed for building resilience into future road pavements and predicting the cost consequences for when this resilience cannot be built-in.

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ACKNOWLEDGEMENTS

The authors wish to thank Austroads and ARRB for providing the funding for the project. The award of the 2013 Austroads Fellowship for the Doctor of Philosophy study is greatly appreciated.

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Dr Gary 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 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 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.
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