Base Course Resilient Modulus for the Mechanistic-Empirical Pavement Design Guide

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Abstract

The mechanistic-empirical pavement design guidelines (MEPDG) recommend use of material modulus in lieu of structural number for pavement base layer thickness design. In this study a methodology was developed to determine a single effective modulus for a base layer using laboratory nonlinear modulus characterization data and a nonlinear finite element response model. With this model, a single representative modulus can be determined by a back calculation procedure in which pavement surface deflections from a nonlinear analysis are matched via an equivalent linear analysis. An equivalent linear analysis using effective moduli for both an unbound base and the subgrade can predict the structural response of an asphalt surface layer in a flexible pavement. It should be possible to utilize these structural response predictions in the assessment of cracking performance of the surface layer. However, caution is warranted in predicting the structural response of the unbound base and subgrade layers using an equivalent linear analysis. Use of an effective modulus for a nonlinear base layer appears reasonable for very thick pavement structures, but appears to under predict vertical strain at the top of subgrade.

INTRODUCTION

Mechanistic-Empirical Pavement Design Guidelines (MEPDG (2004)) for flexible pavement structures recommend use of modulus in place of layer coefficient for unbound aggregate base layer thickness design. Resilient modulus (M_R) and Poisson's ratio (ν) are the two primary input parameters required for thickness design. M_R represents modulus of a material subjected to repeated traffic loading and can be determined in the laboratory via a standard testing protocol (AASHTO T307).

Like soil, unbound base materials are nonlinear and its modulus nonlinearity is dependent primarily on effective confinement stress, loading strain, moisture content (suction) and some other parameters. MEPDG proposes three different levels of M_R input for pavement design. Level 1 M_R input takes material modulus nonlinearity into account, whereas Level 2 and Level 3 M_R input assume material is elastic and assigns a single effective elastic modulus value for the whole layer. However, the nonlinear design analysis response model based on Level 1 nonlinear M_R input has not been calibrated for practical applications. Thus, it seems that a single effective elastic modulus approach using either Level 2 or Level 3 M_R input would be most commonly used in the near future. Therefore, determining this single elastic modulus value is critical for pavement response model analysis.

MEPDG is primarily based on M_R and its determination via the AASHTO protocol. By following the AASHTO T307 testing procedure, material modulus can be characterized from intermediate (10^{-3}%) to larger strains (10^{-1}%) due to the range of deviatoric stresses applied in this test procedure and the external measurement of loads and deformations. Recent research studies in geotechnical engineering (Elhakim and Mayne 2008) have revealed that it is also necessary to consider modulus nonlinearity at small-level strains ($\leq 10^{-3}$%) along with nonlinearity at intermediate to larger strains, to predetermine accurate pavement responses. Since moduli values at small strain levels cannot be determined via the AASHTO protocol due to procedural limitations, small-strain modulus nonlinearity cannot be characterized. Hence, it is plausible that accurate pavement responses cannot be calculated using moduli values obtained via the AASHTO testing protocol. Therefore, it is desirable to consider an alternative procedure that can characterize material modulus nonlinearity at small-level strains along with intermediate to larger strains.

NONLINEAR FINITE ELEMENT MODELING OF BASE LAYER

A main objective was to develop a nonlinear pavement response model that can utilize laboratory testing results and incorporate base modulus nonlinearity with respect to effective stress confinement, loading strain, and moisture content. Our nonlinear finite element solution included an elastoplastic type of hyperbolic model that incorporates strain-dependent stiffness moduli simulating the different reaction of soils to small strain (i.e., strains below 10^{-3}%) and large strains (i.e., strains above 10^{-1}%). Soil modulus behaves elastic at very small-strains (i.e., lower than 10^{-4}%) and decreases nonlinearly with an increase in strain amplitude. A frequently used hyperbolic model to estimate nonlinear modulus reduction in soils, including both small and large strains, is the modified Hardin-Drnevich relationship proposed by Santos and Correia (2001). Two parameters are needed to describe the modulus behavior at any strain: the initial or very small-strain modulus G_{max} and the shear strain level $\gamma_{0.7}$ at $G = 0.7 * G_{max}$.

Flexible Pavement Nonlinear Response Model. The primary basis of our finite element model for flexible pavement is adapted from MEPDG (2004), Appendix-RR (Finite Element Procedures for Flexible Pavement Analysis) as follows:

- Axisymmetric model
- Static single wheel load with 150 mm radius circular cross-sectional area and 550 kPa tire contact stress
- Vertical side boundaries are 10 to 12 radii from center of wheel load and horizontal bottom boundaries are 50 radii below the top of surface layer
- Linear elastic surface asphalt concrete (AC) layer and linear elastic subgrade layer
- Nonlinear base layer

An axisymmetric model with 15-node triangular elements was chosen for the pavement modeling. The size of the elements, i.e., fineness of mesh, was selected such that: 1) there is a smooth continuity of resulting stresses and strains between two adjacent elements, and 2) the time required for processing is not too long. Since the surface AC layer and subgrade layer are considered elastic, the fineness of mesh is critical for the base layer. Vertical side boundaries are at least 12 radii (i.e., > 1.8 m) from load center and the bottom horizontal boundary is at least 50 radii (i.e., 7.5 m) below the top of AC layer. It was also ensured that the location of boundaries has no influence on the resulting deformations by checking that the deformations near boundaries are either zero or almost zero. Vertical side boundaries were fixed horizontally and allowed to move vertically. Horizontal boundaries were fixed both in the horizontal and vertical directions.

A total six different pavement cross-sections with different layer thicknesses were considered for nonlinear analysis (Table 1). Since the focus was on modulus nonlinearity of base layer, the AC surface and subgrade were modeled as linear elastic, and we utilized the MEPDG finite element analysis for material property selection: three elastic moduli for AC (1, 3, 12.5 GPa) and four elastic moduli for subgrade (30, 50, 70, 125 MPa). For base, three materials commonly used in Florida were analyzed: Newberry limerock, Miami limerock, and Georgia granite. The nonlinear modulus relationships for these materials were determined via laboratory resonant column tests that are presented in detail by Ayithi and Hiltunen (2013). The remaining properties required for the finite element model are further described in detail by Ayithi et al. (2011).

Table 1. Pavement Layer Thicknesses

Structure Number	Asphalt Concrete Surface Thickness (mm)	Base Thickness (mm)
1	200	450
2	200	300
3	100	450
4	100	300
5	100	200
6	50	300

BASE LAYER NONLINEAR MODELING RESULTS

With a nonlinear model now available, the next objective was to develop a methodology to calculate an effective, linear elastic modulus for the whole base layer that can approximate known nonlinearities and can be used for MEPDG Level 2 and Level 3 design inputs for practical design applications. Effective modulus determination and the influence of moisture content, subgrade modulus, and overall structural cross-section on effective modulus are discussed as follows.

Effective Base Modulus Determination. To derive an effective elastic modulus value for a base layer, pavement surface deflection was chosen as the matching criterion between a nonlinear and a linear analysis. For nonlinear analysis, both AC surface and subgrade layers are considered linear and the base layer is considered nonlinear. Using the maximum surface deflection obtained from a nonlinear analysis as the criterion, an equivalent, linear elastic modulus value for the whole base layer was determined by trial and error. Once the effective base modulus is determined, pavement responses obtained at critical locations for both linear and nonlinear cases can be compared to examine the influence of the simplification.

To illustrate via an example, nonlinear analysis via the nonlinear pavement response model was performed on Structure 1 (Table 1) with the Newberry limerock base layer at 10% moisture content. The AC surface layer and subgrade layer were considered elastic with moduli of 1000 MPa and 50 MPa, respectively. From the nonlinear analysis a maximum surface deflection of 0.582 mm was obtained under a wheel load of 550 kPa. Keeping the elastic moduli of the surface and subgrade layers the same, an effective modulus for the base layer of 153 MPa was determined by trial and error using a linear analysis for the base layer and producing the same maximum surface deflection of 0.582 mm. For this case, the surface deflection basins for the nonlinear and linear models are plotted in Figure 1 where it is observed that the entire surface deflection basins are in good agreement.

In mechanics, it is well known that the modulus of a particulate material decreases nonlinearly with an increase in strain or load. One of the main objectives of our work was to incorporate this modulus nonlinearity in pavement design. Hence, it is of interest to demonstrate that the effective modulus of a base layer decreases nonlinearly with an increase in load. The results of such a demonstration are shown Figure 2. The analyses were performed for Structure 1 and Structure 4 using Newberry limerock base at 10% moisture content. The moduli of the AC surface layer and subgrade layer were 1000 MPa and 50 MPa, respectively. The effective base modulus at each load level was determined using the procedure described above. It is clearly observed that the effective base modulus decreases nonlinearly with an increase in applied loading pressure. It is also noted that the base modulus is lower for the thinner Structure 4.

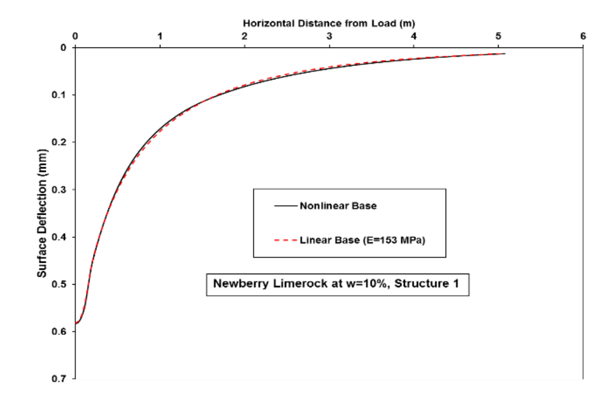

Figure 1. Surface Deflection Basins from Nonlinear and Equivalent Linear Analyses

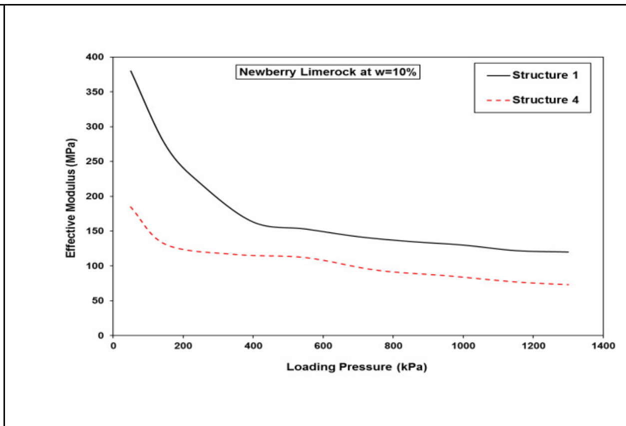

Figure 2. Effective Modulus of Base versus Loading Pressure

Effective Design Moduli. Nonlinear analyses were conducted via the finite element response model on six different pavement structures presented in Table 1 and using material parameters for Newberry limerock, Georgia granite, and Miami. The methodology described above was followed to determine the effective design moduli. By way of example, the results for Newberry limerock and an AC modulus of 1 GPa are presented in Table 2. Ayithi et al. (2011) contains the complete results for all materials.

For Structures 1 to 6 and at constant subgrade modulus, the variation of effective modulus with decreasing moisture content is shown across each row in Table 2. It is clearly observed that effective modulus increases significantly with decreasing moisture content similar to the laboratory results of Ayithi and Hiltunen (2013). Similar results were observed for Georgia granite and Miami limerock (Ayithi et al. 2011). Among the three materials, Miami limerock has the highest effective modulus values. From the laboratory testing results, it was observed that the increase in small-strain modulus with decreasing moisture also is highest for Miami limerock.

By scanning down the columns in Table 2, it can be observed that for any given structure and base moisture content, the effective base modulus increases with an increase in subgrade modulus. This behavior can be explained by fundamentals of pavement mechanics. Pavement deformation is mainly dependent on subgrade modulus and deformation decreases with an increase in subgrade modulus. As the subgrade modulus increases, the magnitude of the deviatoric stresses acting on the base layer decreases. Since base soil modulus is nonlinear and increases with a decrease in deviatoric stress (or shear strain), the base layer effective modulus increases with an increase in subgrade modulus.

Table 2. Effective Moduli (MPa) for Newberry Limerock Base and E_{AC}=1 GPa

Subgrade Modulus (MPa)	Structure	Moisture Content (%)					
		13	12	11	10	8	5.5
30	1	65	79	112	118	142	171
	2	58	70	92	94	118	139
	3	54	67	90	101	108	130
	4	49	60	69	70	76	78
50	1	79	102	140	153	196	230
	2	74	92	120	125	155	178
	3	66	89	112	124	148	168
	4	62	80	108	112	123	132
	5	73	---	100	---	---	102
	6	76	---	90	---	---	107
70	1	90	117	170	175	230	267
	2	85	109	143	149	184	207
	3	73	100	135	142	195	205
	4	71	96	129	135	139	144
125	1	108	157	227	241	310	387
	2	107	147	210	220	278	308
	3	93	141	214	220	281	311
	4	84	127	196	206	228	240
	5	105	---	189	---	---	209
	6	103	---	180	---	---	187

By scanning down the columns in Table 2, it can also be observed that at any given moisture content and subgrade modulus combination, the effective modulus is dependent on structure type, i.e., layer thicknesses. As the layer thicknesses vary from Structure 1 with the thickest section to Structure 6 with the thinnest section, the magnitude of the deviatoric stress transferred from the top to bottom layers also varies. Usually, as the thickness of a layer decreases, the deviatoric stress transferred to the layer beneath it increases, and the corresponding modulus decreases.

Effective design moduli obtained at 8% moisture content for Newberry limerock, 3.5% for Georgia granite, and 4% for Miami limerock are compared with modulus values at their respective optimum moisture contents (OMC) in Figure 3. These plots provide insight on the effect that drying has on the effective modulus of each material. It is observed that the effective modulus of Miami limerock increases at a much faster rate as the material dries out. At OMC, the effective modulus of Miami limerock is much lower than that of Newberry limerock and

Georgia granite, but as the material dries out, its modulus increases significantly faster compared to the other two materials. Toros (2008) and Ayithi et al. (2011) also observed very significant increases in laboratory small-strain modulus results for Miami limerock as the material dries out as compared to Newberry limerock and Georgia granite.

The MEPDG (2004) recommends the following generalized regression model to predict the influence of moisture on resilient modulus (M_R):

$$\log\frac{M_R}{M_{Ropt}} = a + \frac{b-a}{1+EXP(\beta+k_s \cdot (S-S_{opt}))} \quad (1)$$

For coarse grained soils a=-0.3123, b=0.3, β=-0.0401, and k_s=6.8157. It is of interest to determine if the MEPDG model can accurately estimate the modulus of Florida base materials by comparing model predictions with the effective moduli values previously presented. By way of example, Figure 4 compares MEPDG modulus predictions with effective moduli for Newberry limerock, and for selected pavement structures and subgrade moduli shown in the legend. The moduli are shown normalized using the modulus at optimum moisture content (E_{opt} or $M_{R\ opt}$), and the results are plotted versus the reduction in degree of saturation due to drying from optimum moisture content. It is observed that the modulus value from the MEPDG model can increase up to two times upon drying from optimum moisture content, whereas the effective moduli values presented herein experience a larger increase. In general, for structures with low subgrade modulus (50 MPa), effective moduli are near the MEPDG model values. However, as the subgrade modulus increases, E/E_{opt} values are much higher than those from the MEPDG model, and up to 3.5 times for Newberry limerock. The corresponding results were 2.5 times for Georgia granite and 47 times for Miami limerock. From these observations it can be concluded that the MEPDG model does not well represent the moisture/suction effect for Florida base materials. Use of the MEPDG model would be a conservative estimate at best.

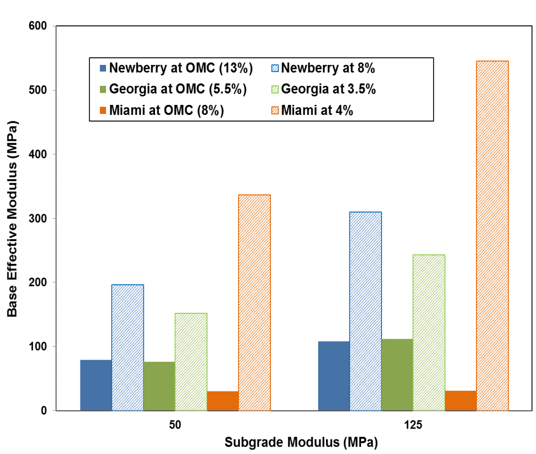

Figure 3. Effetive Moduli of Three Base Materials at Two Moisture Contents and Two Subgrade Moduli for Structure 1

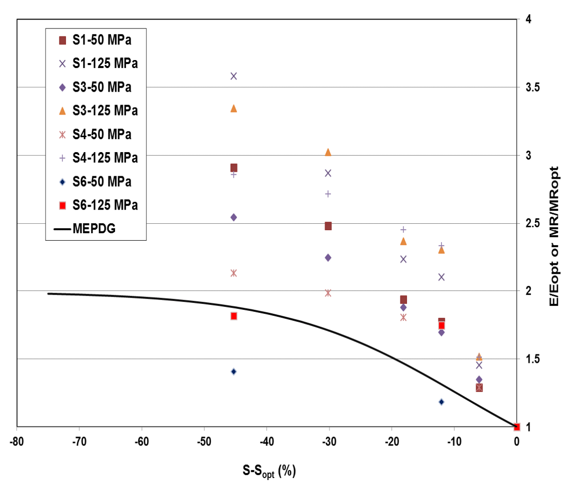

Figure 4. Comparison of Newberry Limerock Effective Base Moduli with MEPDG Model

Comparison of Nonlinear and Equivalent Linear Responses. A methodology to determine an effective design modulus for a base layer was developed by equating maximum surface deflection between a nonlinear and linear response analysis. It was also demonstrated that the complete surface deflection basin generated from a nonlinear analysis and a corresponding equivalent linear analysis match well. As a next step, it is of interest to compare other pavement responses generated from the nonlinear and equivalent linear analysis models to more fully assess the applicability of the effective modulus in lieu of a nonlinear analysis. For this purpose, pavement responses at critical locations obtained from nonlinear and corresponding equivalent linear analysis are compared.

Responses obtained from nonlinear and corresponding equivalent linear analyses at several locations within a pavement structure were as follows:

- Surface deflection
- Horizontal stress (σ_{xx}) and strain (ε_{xx}) at top of AC layer
- Horizontal stress (σ_{xx}) and strain (ε_{xx}) at bottom of AC layer
- Vertical stress (σ_{yy}) and strain (ε_{yy}) at top of base layer
- Vertical stress (σ_{yy}) and strain (ε_{yy}) at bottom of base layer
- Vertical stress (σ_{yy}) and strain (ε_{yy}) at top of subgrade layer

The basis for selecting these responses for comparison is found in the fundamentals of pavement mechanics. Surface cracking and rutting are two important distresses that occur in pavement structures. Surface cracking is primarily dependent on the horizontal strain (ε_{xx}) at the bottom of AC layer, and rutting is dependent on vertical strain (ε_{yy}) at the top of subgrade layer. Comparison of these two responses for nonlinear and linear analyses can illustrate whether adopting an effective modulus in place of nonlinear analysis would influence the rutting and cracking performance prediction of a pavement. Surface deflection was chosen as the criterion of equivalency between the nonlinear and equivalent linear analysis and a comparison will illustrate the accuracy of the match. The remaining stress and strain responses provide further information regarding how well the stresses and strains at different layer intersections agree between the nonlinear and equivalent linear analyses.

A complete demonstration of pavement responses obtained from nonlinear and equivalent linear analysis of selected pavement structures with an AC surface modulus of 1000 MPa, a subgrade modulus of 50 MPa, and base materials at specified moisture contents are presented in Ayithi (2011). Because it is particularly important, the horizontal strain (ε_{xx}) at the bottom of AC layer of Structure 1 and Structure 4 with different base moisture contents is compared in Figure 5 for Newberry limerock. Similarly, the vertical strain (ε_{yy}) at the top of subgrade layer is shown in Figure 6 for Newberry limerock.

From the surface deflection profiles (see example previously presented in Figure 1), it was observed that the surface deflection profiles for nonlinear and equivalent linear analyses match well. This demonstrates that the procedure for determining an effective modulus based upon matching the maximum surface deflection also results in a more general matching of the complete surface deflection profile.

From the comparison plots of horizontal tensile strain (ε_{xx}) at bottom of AC layer (Figure 5), it can be observed that the nonlinear analysis and the equivalent linear case with an effective base modulus produce similar results. This suggests that an equivalent linear analysis can produce an accurate prediction of pavement response in the AC surface layer. This may also suggest that the cracking performance of a flexible pavement can be reasonably assessed via a linear elastic analysis of the pavement so long as appropriate effective elastic moduli are chosen for the analysis.

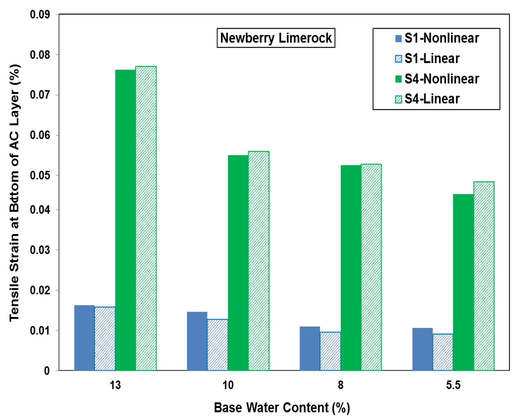

Figure 5. Horizontal Tensile Strain at Bottom of AC for Structures 1 and 4

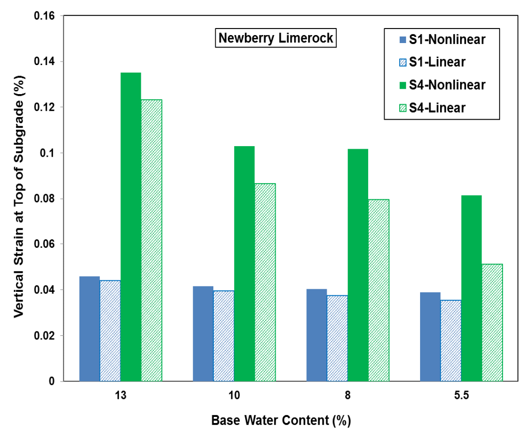

Figure 6. Vertical Compressive Strain at Top of Subgrade for Structures 1 and 4

Comparison plots of vertical strain (ε_{yy}) at the top of subgrade for nonlinear and equivalent linear cases are compared in Figure 6. In the case of Structure 1, it can be observed that the nonlinear analysis and the equivalent linear case with an effective base modulus produce similar results. In the case of Structure 4, the top of subgrade strains from the nonlinear analysis are higher than the corresponding equivalent linear analysis, and this difference increases with a decrease in moisture content. This suggests that the base material nonlinearity becomes more important with a decrease in moisture content. Since Structure 4 is thinner than Structure 1, this also suggests that material nonlinearity increases as the structure thickness decreases, which should be expected. Thus, as the base nonlinearity increases with a decrease in structure thickness or a decrease in base layer moisture content, an effective elastic modulus based upon matching surface deflection should be used with caution. According to pavement mechanics, vertical strain at the top of subgrade is a strong indicator of rutting performance. Thus, the differences in strain might suggest that a linear elastic analysis would overestimate rutting performance. However, this could only be demonstrated by comparing a rutting performance analysis conducted via a suitably-calibrated nonlinear model with a similar model based upon a linear elastic analysis. Such a comparison is beyond the scope of this investigation. Finally, it should also be noted that the differences in strain found in these comparisons are probably accentuated due to the choice of a relatively soft subgrade modulus of 50 MPa. A softer subgrade is expected to increase the nonlinear behavior similar to the effect of decreasing the structure thickness.

CONCLUSIONS

Utilizing laboratory testing data as material inputs, a nonlinear finite element response model that can account for modulus nonlinearity was developed. Based upon the base layer modeling and analysis results, the following conclusions are appropriate:

- The finite element methodology is an effective means for assessing the effects of unbound pavement material nonlinearity on the structural response of pavements.
- Practical pavement design utilizing the MEPDG will require input of a single modulus value to represent unbound base and subgrade materials. A representative modulus can be determined by a backcalculation procedure in which pavement surface deflections from a nonlinear analysis are matched via an equivalent linear analysis.
- The nonlinearity of unbound base materials is significant and the single effective modulus will vary over a range of conditions, including the moisture content of the base, pavement layer thicknesses, and the modulus of the subgrade.
- There is a significant effect of moisture on the modulus of base materials used in Florida, particularly those composed of limerock. The modulus/moisture relationship employed in the MEPDG under predicts the significant increase in modulus of Florida limerock base materials when dried below OMC. Use of the MEPDG model will be conservative.

ACKNOWLEDGEMENTS

The Florida Department of Transportation supported the work described herein, and the authors thank the Project Panel of David Horhota, Bruce Dietrich, and Rodrigo Herrera for their technical support and encouragement.

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