Seismic Approach to Quality Management of HMA

MnDOT Contract No. 1034287

Report – 2nd Quarter, 2020

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SUMMARY

We provide a progress report for the 2nd quarter of 2020. Based on feedback regarding the length and detail of the 1st quarter report, we have taken a new, simplified format. This report summarizes key topics regarding work in progress. Details and supporting documents can be found on the project website. The overall progress has been summarized by month and has also been posted on the "Progress" page of the project site.

Progress summary of the previous quarter (Q1-2020) was presented in the report and appendices posted online. This report summarizes the progress made since then in those tasks specified in the Scope of Work (SOW), which are categorized into the following five (5) tasks:

- Task #1: Project Management and Administration
- Task #2: Hardware Development (Seismic Data Acquisition System) & Testing
- Task #3: Software Development & Testing
- Task #4: Delivery and Demonstration of Seismic Data Acquisition System and Software
- Task #5: Final Report

Progress on the first 3 tasks (#1 – #3) are summarized in this report. First, we provide brief snapshots of monthly progress. Second, quantified indices are tabulated for all three tasks for both prime (Park Seismic LLC) and sub (Norrfee Tech, AB) contractors. Lastly, the project projection for the next quarter (Q3-2020) is prepared by compiling feedback and plans from all participants.

MONTHLY PROGRESS

April, 2020

- **Project Management and Administration (Task #1)**

  The 1st quarterly report (Q1-2020) was prepared and submitted by all (4) project participants. It was posted on the web page by report and appendices.

  The monthly meeting was organized via Skype and the minutes were posted on the web page by the administration staff. The monthly invoicing and payment to the sub contractor had been managed by the staff. The project web site had been updated a few times each month to reflect the progress status.

- **Acquisition System Being Constructed (16-bit 64-channel AD converter) (Task #2)**

  We have begun building the first (primary) hardware component (AD converter). It is the NI PXI System that can acquire a maximum of 64 channels with a 16-bit dynamic range. A description of the component items and corresponding specifications are listed here. It is "parallel prototyped" by referencing to the previous system developed for a similar project at Lund University (LTH) in 2019 ("SYS-RYD-2019") (see photo on the web). The new system is more compact in size and lighter in weight than existing systems. It consists of two 32 acquisition boards allowing a maximum of 64-channel acquisition, mounted in a PXI rack. It will also include additional capacities of recording GPS coordinates and temperature of the HMA surface at the measurement points. The GPS receiver and infra-red (IR) temperature sensor are shown in a photo on the web and are at this point only borrowed from another project for prototyping purposes but will later be acquired also for this project.

- **Software Approach to Attenuate Impact-Generated Sound Wave (Task #3)**

  When using microphones as receiver to record the leaky-mode surface waves that are "leaked" from the HMA pavement surface, all ambient sound waves are also recorded as noise. The most troublesome sound wave is the one generated at the time of impact. It is always generated when an impact is applied on the pavement surface to generate seismic (surface) waves and it is very strong in comparison to the level of signal seismic waves as shown in Figure 1 on this web page. If not properly handled, it can cause a low signal-to-noise (SN) ratio at the high-frequency part of seismic signal (e.g., > 20 kHz) that can ultimately lead to a reduced accuracy in the evaluated seismic velocity (Vs) of the pavement layer. In addition, it can completely mask the useful part of the Lamb dispersion trend at low frequencies (e.g., 1-10 kHz) that is critically important to accurately evaluate the thickness (H) of the pavement layer. Therefore, it is crucial to reduce the level of this type of sound wave not only at the time of data acquisition but also during the data analysis steps. This is especially important when dealing with an HMA pavement (rather than a concrete pavement) because of the more significant attenuation of seismic waves occurring with the HMA pavement as noticed in Figure 1b on this web page. A possible effort to reduce the level at the time of data acquisition has been outlined in one of the documents from previous month's progress. A description of the test results obtained by using different software approaches is provided here.

May, 2020

- **Project Management and Administration (Task #1)**

  The monthly meeting was organized via Skype and the minutes were posted on the web page by the administration staff. Monthly invoicing and payment to the sub contractor had been managed by the staff. The project web site has been updated each month to reflect progress.

- **Acquisition System Being Constructed (16-bit max. 64-channel AD converter) (Task #2)**

  The system is under construction and scheduled for a field test in June-July by using the MEMS microphone receiver array used for SYS-RYD-2019.

- **Software Approach to Attenuate Air Waves (Continued Development) (Task #3)**

  Direct air (sound) waves generated at and coming from the impact point are the most troublesome noise for the microphone measurement of leaky-mode Lamb waves that have to be suppressed by means of both acquisition and post-acquisition efforts. In previous summary of the development, several different multichannel data-processing approaches were considered for their effectiveness in attenuating the air waves (noise) while preserving the Lamb waves (signal) as mush as possible. They included fk-filtering, muting, and fk-muting approaches. They all turned out having pros and cons for the final goal of velocity (Vs) and thickness (H) evaluation of the HMA layer. This indicates all of them can be useful in different combinations under different condition of the acquired data; e.g., data with a low SN ratio vs. a high SN ratio, etc.

Our work has enabled a further enhancement of the process using the linear-move-out (LMO) approach. This report summarizes a new successful approach that uses a moving-window LMO stack to attenuate the air wave event of a specific propagation velocity (e.g., 334 m/s). Test results with synthetic and real field data sets indicate the effectiveness is superior over the previous conventional approaches (e.g., fk, mute, etc.), especially for the Impact Echo (IE) method that can evaluate the thickness (H) independently from the analysis of propagating waves. This part of the result (IE) will be described in the summary part of the next month (June, 2020).

- **TDMS Data Format (Task #2 & #3)**

Technical Data Management Solution (TDMS) is a data format commonly used for an output from hardware components manufactured by NI (formerly called National Instruments). This project uses NI hardware components to build the acquisition system.

Although it seems to contain unnecessary components that can slow down data transmission speed between the hardware and the onboard software modules, the TDMS format will be considered for possible adoption after evaluating its structural format.

June, 2020

- **Project Management and Administration (Task #1)**

The monthly meeting was organized via Skype and the minutes were posted on the web page by the administration staff. The monthly invoicing and payment to the sub contractor had been managed by the staff. The project web site has been updated each month to reflect progress.

- **Acquisition System Being Constructed (16-bit max. 64-channel AD converter) (Task #2)**

The system is under construction and scheduled for a field test in the future by using the receiver array used for SYS-RYD-2019 when the configuration for 1D array is determined.

- **Thickness (H) Evaluation [Lamb Dispersion (A0) and Impact Echo (IE) Approaches] (Task #3)**

Thickness (H) of HMA layer can be evaluated from the same Lamb-wave dispersion curve (A0) that is used to evaluate the shear-wave velocity (Vs). On the other hand, it can also be evaluated from the spectral characteristics of obtained seismic data through the Impact Echo (IE) method. Both approaches are examined during the month of June, 2020.

In theory, thickness of HMA layer (H) can be measured by the same Lamb dispersion curve, the fundamental anti-symmetric (A0) mode, that is used to evaluate the shear-wave velocity (Vs) of the layer. An A0 curve consists of a curved part that has increasing phase velocity with frequency and occurs at the low-frequency side of the curve (e.g., 1-10 kHz) and a relatively flat part with a fairly constant phase velocity that occurs at the higher-frequency side of the curve (e.g., 10-50 kHz). The constant phase velocity of the curve corresponds to the Rayleigh-wave velocity (VR) of the HMA layer, which is about 92% of the shear-velocity (Vs) for the common range of Poisson's ratio (e.g., 0.15-0.35). For a given HMA layer of VR, the onset frequency of the curved part from the flat part of the curve changes with the thickness (H) of the layer; i.e., the thicker layer will result in the lower onset frequency. In consequence, the overall shape of the curved part will also change with H. All these properties of A0 curve are graphically illustrated in this report.

Conventional seismic measurements through contact approach (e.g., accelerometer) well depicted both curved and flat parts of A0 curve. However, the non-contact rolling measurements by using MEMS microphones did not show clear definition of the curved part although they delineated the flat part with superb quality. It is believed that this can be closely related to the spectral characteristics of the light impact source that tends to generate more energy at higher frequencies (e.g., 10-50 kHz). This, however, will be verified soon in the near-future when more microphone data sets are collected by using multiple impact sources of different impact energy. However, the phenomenon may also be related to the near-field effect of surface waves as well as attenuation properties of the pavement layer.

In this report, these two aspects (i.e., near-field effect and attenuation) are examined by using field data sets acquired in the past by using both contact (i.e., accelerometer + hammer) and non-contact (i.e., microphones + bouncing ball) approaches. In parallel to the Lamb curve (A0) approach to evaluate the thickness (H), another independent approach that works on the spectral characteristics of the measured seismic wavefields is now considered. It is the Impact Echo (IE) approach that measures the spectral peak that is associated with the seismic resonance within the solid material. The peak occurs at the resonance frequency (fr) that is determined by the P-wave velocity (Vp) and thickness (d) of the layer; i.e., fr=BVp / (2d) where B is called a correction factor that slightly changes with Poisson's ratio, but is commonly set to a constant value of 0.96.

First, two different approaches are tested to construct the amplitude spectrum; i.e., stacking individual amplitude spectrum from each channel's data [frequency-domain stacking (FDS)] and stacking all channels seismic data first and then construct the amplitude spectrum [time-domain stacking (TDS)] (Ryden, 2016). It turned out TDS is far more effective than the former. Second, the most recent development by Bjurstrom and Ryden (2016) that applies negative phase velocity to construct a frequency-phase velocity spectrum is tested. This approach (Bjurstrom and Ryden, 2016) turned out highly effective and will be used as the main IE method in this project.

The future plan is to apply both approaches (A0 curve and IE) to evaluate the thickness (H). Then, both values will be used to come up with an average value (Have) by applying an appropriate weight to each value based on a few quality factors. In this report, the general scheme of the IE method is briefly explained. Then, a synthetic seismic record is generated to be used to test each type of IE approach. Finally in this report, Bjurstrom and Ryden (2016) is used for real data sets from both contact and non-contact approaches.

- **TDMS Data Format (Task #2 & #3)**

A project to build a C++ module to read the TDMS file of seismic data saved by the acquisition system being developed at Norrfee Tech is launched. The project will complete a separate C++ software module that reads TDMS files and converts them into the ParkSEIS data format, which is the standard format for the software package being developed.

PROGRESS BY TASKS AND NUMBERS

The entire work executed to accomplish the project goal is categorized into five (5) tasks (Tasks #1 – #5) as previously listed. In this report, the progress accomplishments made by both prime and sub contractors are described in the first 3 tasks (#1 – #3) by using the quantified indices used in the progress report form (Exhibit E in the project contract) submitted each month. These values are presented in tables and then graphically displayed by using charts in the next two pages, respectively.

Work Completed – Prime* Contractor

This Period (%)

Task	Previous Quarter (Q1-2020)			This Quarter (Q2-020)		
	January	February	March	April	May	June
#1	9.6	9.2	5.4	21.2	4.2	2.3
#2	0	0	0	0	0	0
#3	2.3	4.7	7.5	4.4	11.9	6.3

To Date (%)

Task	Previous Quarter (Q1-2020)			This Quarter (Q2-020)		
	January	February	March	April	May	June
#1	9.6	18.8	24.2	45.3	49.6	51.9
#2	0	0	0	0	0	0
#3	2.3	7	14.5	18.9	30.8	37

Work Completed - Sub** Contractor

This Period (%)

Task	Previous Quarter (Q1-2020)			This Quarter (Q2-020)		
	January	February	March	April	May	June
#1	30	5	5	10	2.5	2.5
#2	0	1.9	0.8	1	2.4	5.8
#3	0	0	0	6.7	13.3	0

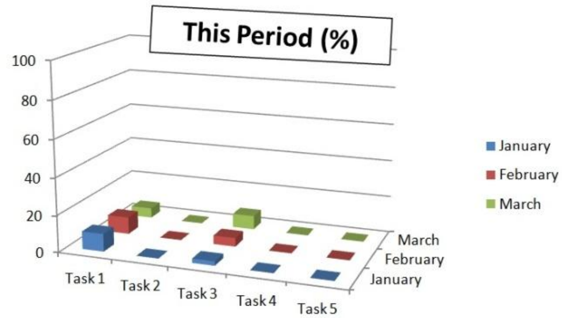
To Date (%)

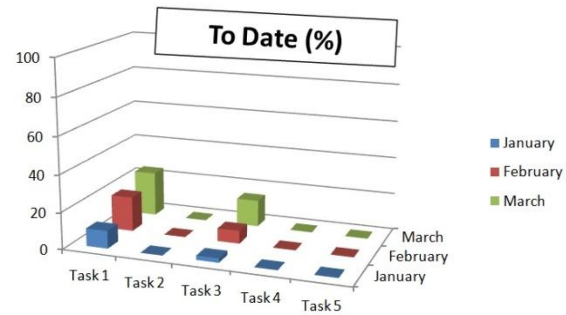
Task	Previous Quarter (Q1-2020)			This Quarter (Q2-020)		
	January	February	March	April	May	June
#1	30	35	40	50	52.5	55
#2	0	1.9	2.7	3.8	6.2	12
#3	0	7	0	6.7	20	20

*Park Seismic LLC, **Norrfee Tech, AB

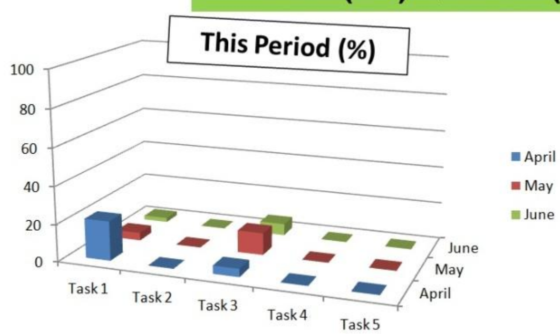
Prime Contractor (Park Seismic LLC)

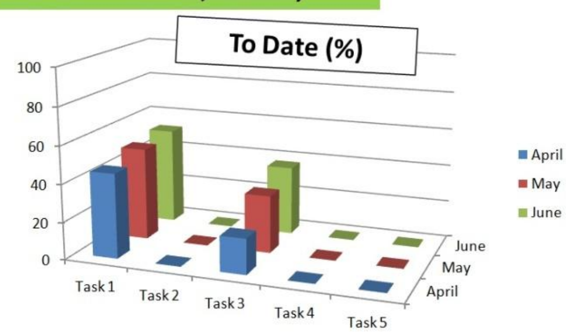
Previous (1st) Quarter (January – March, 2020)





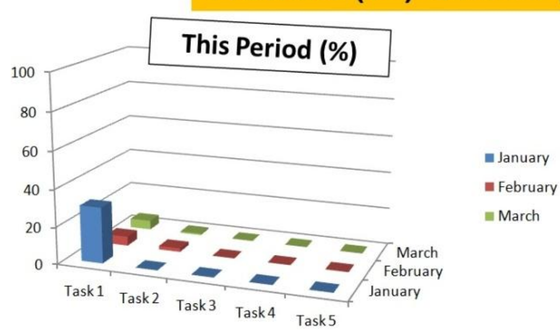
This (2nd) Quarter (March – June, 2020)

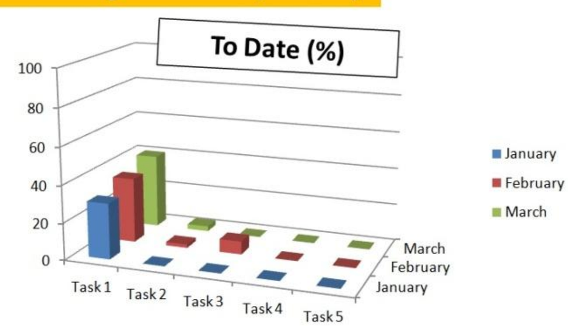




Sub Contractor (Norrfee Tech, AB)

Previous (1st) Quarter (January – March, 2020)





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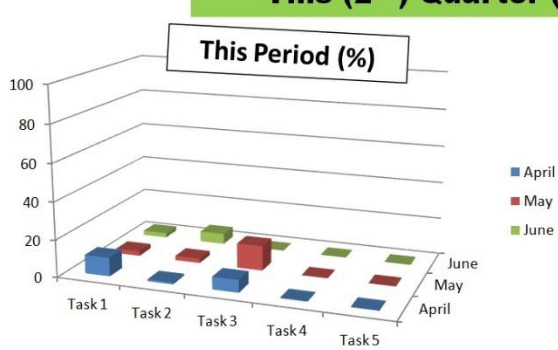

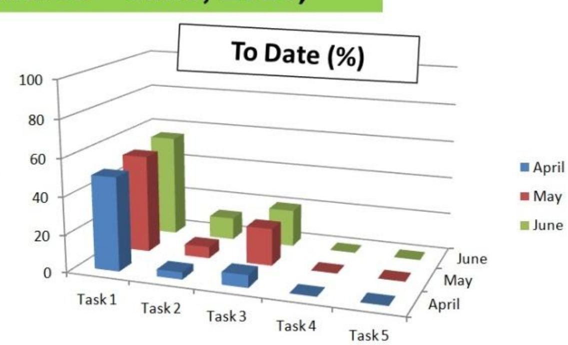

PROJECT PROJECTION

Projections made in the three tasks (#1 – #3) for the next three months (Q3-2020) are summarized below.

- **Task #1: Project Management and Administration**

  Progress for all three tasks will be continuously summarized each month and posted on the web. The monthly meeting will continue and the minutes will be available online. The overall summary of the progress and subsequent projection for the remainder of the project period, as of August, 2020, will be presented during the NRRA webinar scheduled on September 3, 2020. Due to COVID-19, the joint field test (JFT) scheduled on October, 2020, at Lund, Sweden, is being considered to take place remotely for a prolonged period (e.g., 1 week) by a series of brief field tests executed by Norrfee Tech at Lund followed by online discussion and calibration meetings with the software developer (Park Seismic). This will be continuously discussed and finalized during the upcoming monthly meetings. As the total number of channels for the final system may be extended to 96 (from 64) channels and there are changes in travel plan, an adjustment in budget allocation is also being considered, which may necessitate the submission of an amended budget proposal.

- **Task #2: Hardware Development & Testing**

  New field tests with the previous hardware system will be performed during August 2020. These tests will give us the information necessary to arrive at several design decisions regarding the part of the hardware from the microphones to the A/D converters, i.e. the possible hardware summation of microphone channels with the aim of suppressing the direct impact air wave, the length of the cabling and the choice of microphone array mounting apparatus (trailer or the less flexible bicycle rack). Once the results are in from the previous system, the development of new system for this project will be continued with touch ups of the hardware close data acquisition software, manufacturing of the new microphone array, cabling and connectors and microphone mounting apparatuses.

- **Task #3: Software Development & Testing**

  It will be continued to improve the accuracy and speed in the evaluation of velocity (Vs) and thickness (H) through fully automated algorithms. It seems the pre-processing steps that evaluate and improve the overall signal-to-noise (SN) ratio of the acquired seismic wavefields are the crucial components in the QA/QC part of the analysis software package, which was not taken into consideration previously. Corresponding algorithmic development and subsequent refinement will continue as more diverse field data sets are obtained. Accordingly, the approaches to attenuate recorded air (sound) waves will also be continuously updated and refined, which will contribute to the improved accuracy in Vs and H evaluations.

  The Impact-Echo (IE) method to separately evaluate the thickness (H) will be further improved in its accuracy and automatic calculation mode by fully utilizing advantages in the multichannel acquisition and analysis approaches. The relative accuracy will be compared to that of the Lamb-dispersion-curve (A0) approach as soon as more field data sets are obtained.

All analysis components for Vs, H, and QA/QC evaluations will be fully automated. In addition, they will be tested for the parallel process as a means to reduce the overall computation time, which will be critical for the in-field analysis package.