ACTIVE AND PASSIVE-SOURCE SURFACE WAVE INVESTIGATION TO CHARACTERIZE S-WAVE VELOCITY STRUCTURE OF DWELLING MOUNDS AND UNDERLYING GEOLOGIC STRATA IN THE GRONINGEN GAS FIELD, THE NETHERLANDS

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The Groningen gas field in the northwestern portion of the Netherlands is subject to ground subsidence and induced seismicity associated with extraction of natural gas over the past 60 years. Some buildings in the area are constructed on dwelling mounds (terps or wierden), many of which were constructed several centuries ago to manage flooding. To incorporate the wierden into the seismic risk model for the Groningen area, seismic site characterization was conducted on nine dwelling mounds to characterize the S-wave velocity structure of both the dwelling mounds and underlying geologic units.

Array microtremor and 1D and 2D MASW data (both Rayleigh and Love wave) were acquired at each site using a nodal seismic system and 3C 5 Hz geophones. Active source Rayleigh wave data were acquired using sledgehammer, accelerated weight drop (AWD), and explosive energy sources. Active source Love wave data were acquired using a 90 kg electromechanical vibrator as the energy source. Initial survey design consisted of 302 3C geophones deployed along four linear arrays intersecting at a common station and aligned in a "star" pattern. Both array microtremor and MASW data were acquired along these arrays. Survey design was later modified to a 25-station circular array (center point and four circular arrays with radii of 10, 25, 50 and 120 m) for array microtremor data acquisition and a single 120 m linear array (121 3C geophones at 1 m spacing) for MASW data acquisition.

Typically, a minimum of 24 hours of array microtremor data was acquired at each site and data analysis was conducted using six to eight 2-hour time blocks. Rayleigh and Love wave dispersion data were reduced from the array microtremor data using a combination of the high-resolution frequency-wavenumber transform (HRFK), Rayleigh three-component beamformer (RTBF) and extended spatial autocorrelation (ESAC) techniques.

2D MASW data were reduced using the common midpoint cross correlation gather approach with some modifications to allow for combination of multiple dispersion curves from different source types and/or different offset ranges at each model station. 2D S-wave (V_S) velocity models were developed from both Rayleigh and Love wave dispersion data to characterize V_S structure of the upper 10 to 15 m. 2D MASW Rayleigh and Love wave dispersion data from near the center of each array were combined with 1D MASW dispersion data extracted from AWD and explosive source seismic data and array microtremor data to develop 1D V_S models to a depth of between 100 to 300 m at each site. VS models were developed using both local and global search inversion of effective mode Rayleigh wave, fundamental mode Rayleigh and Love wave, multi-mode Rayleigh wave, joint Rayleigh/Love wave dispersion data, as applicable. About 1,500 1D V_S models were provided for each site to quantify non-uniqueness and be used for ground response analysis.

S-wave velocity of the dwelling mounds (upper several meters) typically ranges from about 60 to 100 m/s with moderate lateral velocity variability often observed. Beneath the dwelling mounds, modeled V_S at the nine sites increases with depth from about 100 m/s to greater than 200 m/s in the 10 to 20 m depth range, greater than 400 m/s in the 60 to 110 m depth range, and slightly greater than 600 m/s in the

230 to 300 m depth range. The average shear wave velocity of the upper 30 m (V_{S30}) at the nine sites ranged from about 159 to 186 m/s with 7 if the 9 sites having V_{S30} in the 168 to 175 m/s range. The coefficient of variation of V_{S30} for the 1,500 equivalent VS models presented for each site was typically only several percent.