Program manual No. 7

Getting started guide for “TLEM1_3”

by

Kazuo KONAGAI

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Getting started guide for TLEM1_3

Thin-Layered-Element Method for Dynamic Soil - Pile Group Interaction Analysis

Kazuo KONAGAI

1. INTRODUCTION

Thin Layer Element Method was originally developed by Tajimi and Shimomura in 1976 to describe layered soil - embedded foundation interaction in a rigorous manner. Konagai (2003) then formulated a stiffness matrix for an upright beam, which is practically equivalent to a group of piles beneath a rigid pile cap. Given these formulations, “TLEM1_2” was developed in 1999 to analyze dynamic layered soil - pile group interaction effects in the frequency domain.

2. WHAT CAN WE DO WITH “*TLEM*”?

A soil-structure system is divided into two substructures, the super-structure and the unbounded soil extending to an infinity; the latter includes an embedded foundation as illustrated in **Fig. 2.1**. In the lower substructure of soil, an earthquake will cause soil displacements $\{\boldsymbol{u}^f\}$. The foundation embedded in this soil deposit, however, do not follow the free-field deformation pattern. This deviation of the displacements from the free-field soil displacements $\{\boldsymbol{u}^f\}$ is denoted by $\{\boldsymbol{u}^s\}$. The mass of the super-structure then causes it to respond dynamically, and the forces $\{\boldsymbol{p}\}$ transmitted to the lower substructure of soil and foundation will produce further deformation of soil $\{\boldsymbol{u}^r\}$ (***inertia interaction***) that cannot occur in a fixed base structure. Thus, the displacements of soil $\{\boldsymbol{u}\}$ are eventually expressed by the following equation as:

$$\{\boldsymbol{u}\} = \{\boldsymbol{u}^f\} + \{\boldsymbol{u}^s\} + \{\boldsymbol{u}^r\} \tag{2.1}$$

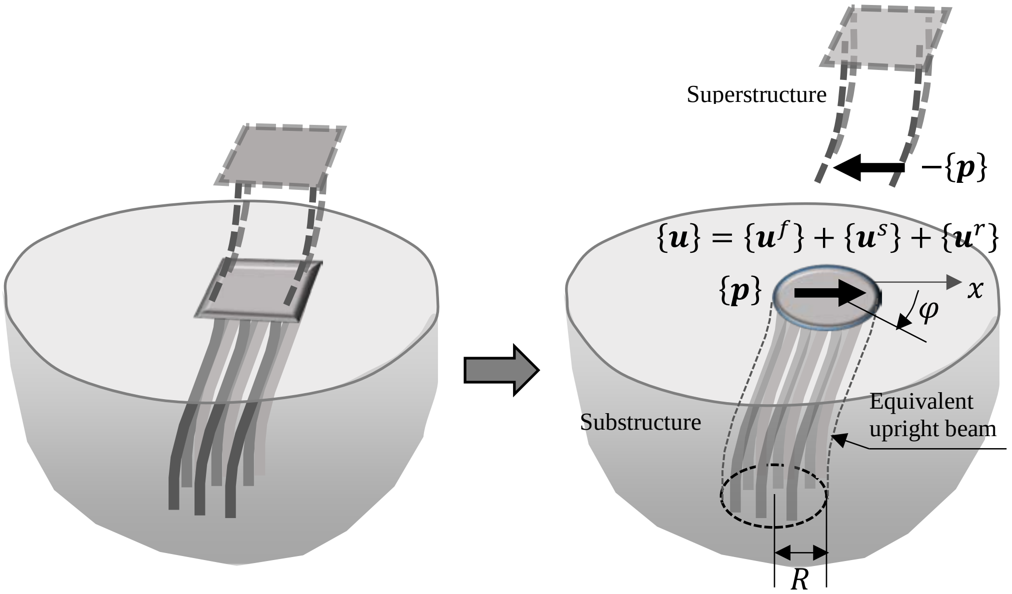
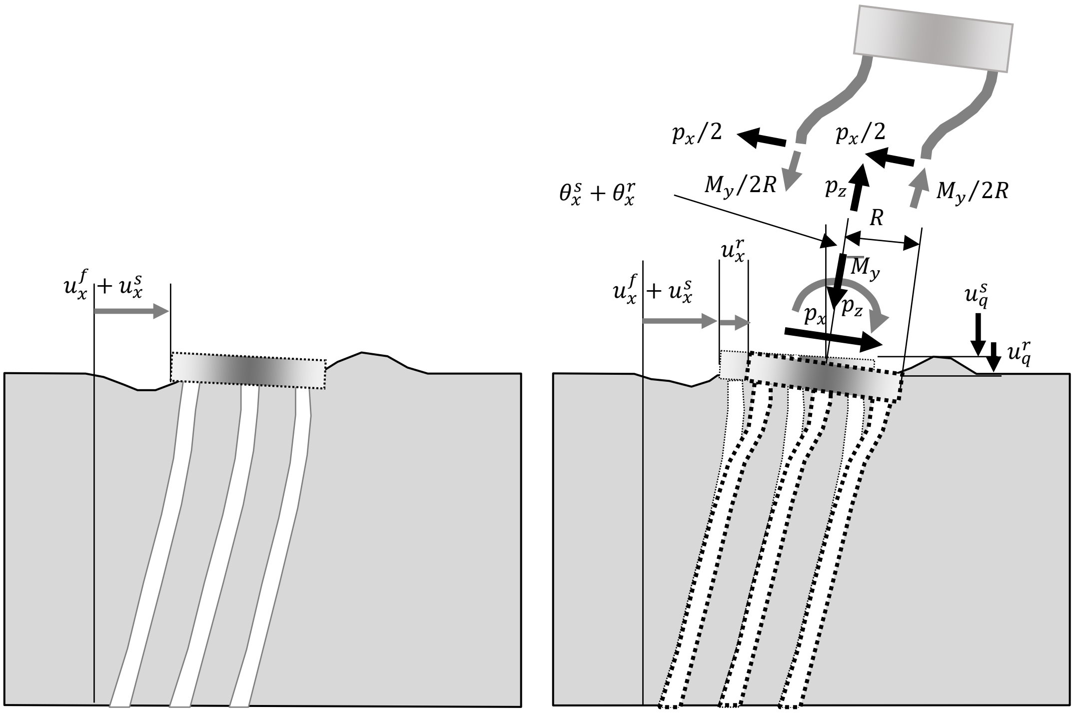


Fig. 2.1 Super and sub-structures to analyze



(a) Kinematic soil-foundation interaction (b) Inertia soil-structure interaction

Fig. 2.2 Kinematic and inertia soil-pile interaction

In **TLEM**, a pile group is approximated by a single equivalent beam with a circular cross-section of radius R embedded upright in a stratified soil, and this foundation is shaken in *x* direction, which direction is set as the polar axis (**Fig. 2.1**). This assumption calls for the displacement components of both the foundation (upright single beam) and its side soil to be proportional to either $\cos\varphi$ or $\sin\varphi$ with φ as the angular coordinate. Components of inertia interaction displacements $\{\boldsymbol{u}^r\}$ at the top rigid pile cap are denoted by u_x^r, u_q^r $(= R\cdot\theta_y^r)$ and u_z^r respectively (**Fig. 2.2**).

The interaction forces $\{\boldsymbol{p}\}$ $(=\{p_x \quad p_q(=M_y/R) \quad p_z\}_{top}^T)$from the super-structure causes the inertia interaction motions $\{\boldsymbol{u}^r\}_{top}$ $(=\{u_x^r \quad u_q^r(=R\cdot\theta_y^r) \quad u_z^r\}_{top}^T)$ in the frequency domain as:

$$\begin{Bmatrix} u_x^r \\ u_q^r(=R\cdot\theta_y^r) \\ u_z^r \end{Bmatrix}_{top} = \begin{bmatrix} H_{xx} & H_{xq} & 0 \\ H_{qx} & H_{qq} & 0 \\ 0 & 0 & H_{zz} \end{bmatrix} \begin{Bmatrix} p_x \\ p_q(=M_y/R) \\ p_z \end{Bmatrix}_{top} \tag{2.2}$$

$$\text{with} \begin{bmatrix} H_{xx} & H_{xq} & 0 \\ H_{qx} & H_{qq} & 0 \\ 0 & 0 & H_{zz} \end{bmatrix} = [\boldsymbol{H}] = [\boldsymbol{S}]^{-1} \tag{2.3}$$

where $[\boldsymbol{H}]$ and $[\boldsymbol{S}]$ are the flexibility and the stiffness matrices at the rigid pile cap.

This program provides the following data sets in the frequency domain:

1) **<u>Free-field ground motion</u>** $\{\boldsymbol{u}^f\}$ of a horizontally layered soil subjected to a constant-amplitude sinusoidal shake given to its bedrock
2) **<u>Motions of the pile group</u>** $\{\boldsymbol{u}^f\}+\{\boldsymbol{u}^s\}$ caused by the incoming free-field ground

motion $\{\boldsymbol{u}^f\}$.

3) **Kinematic displacement effect** $T_{e,sway}$, $T_{e,rocking}$ and $T_{e,vertical}$ transfer rates of free-field ground motion to grouped pile foundation. These rates are evaluated at the ground surface level, namely:

$$T_{e,sway} = \left(\frac{u_x^f + u_x^s}{u_x^f}\right)_{top} \tag{2.4a}$$

$$T_{e,rocking} = \left(\frac{u_q^s}{u_x^f}\right)_{top} \tag{2.4b}$$

$$T_{e,vertical} = \left(\frac{u_z^f + u_z^s}{u_z^f}\right)_{top} \tag{2.4c}$$

Note that definitional equation (2.4b) of $T_{e,rocking}$ has no u_q^f but u_x^f as the denominator, because the incoming ground motion has practically no rotational component u_q^f. The horizontal component of the incoming ground motion u_x^f, only when transferred to the pile foundation, can cause the pile cap to rotate.

4) **Flexibility components** H_{xx} , H_{xq} ($= H_{qx}$), H_{qq} , H_{zz} and **stiffness components** S_{xx}, S_{xq}, S_{qq}, S_{zz} in the flexibility and the stiffness matrices, respectively (See equations (2.2) and (2.3)).

Equivalent single upright beam

The soil and N_p piles are divided into N_L horizontal slices as shown in **Fig. 2.3**. The following assumptions are adopted to derive the stiffness matrix for the equivalent single upright beam:

(1) Pile elements within a horizontal soil slice are deformed all at once keeping their intervals as they are, and the soil caught among the piles moves in a body with the piles. The cross-section A_g of the equivalent single upright beam, thus, comprises both the firmly joined piles and the soil.

(2) Frictional effects due to bending of piles (moments exerted on each pile from the surrounding soil) are ignored.

(3) Top ends of the piles are fixed to a rigid cap.

(4) All upper or lower ends of the sliced pile elements arranged on each cut-end of a soil slice remain on one plane AA'(Note this assumption does not necessarily mean that each pile's cross-section remains in parallel with this plane AA'. See **Fig. 2.3** next page).

This plane AA' works like a "**rigid coupling rod for locomotive wheels**" allowing all ends of pile slices spaced at regular intervals to rotate freely. From this viewpoint, the equivalent single upright beam is neither Euler–Bernoulli nor Timoshenko beam.

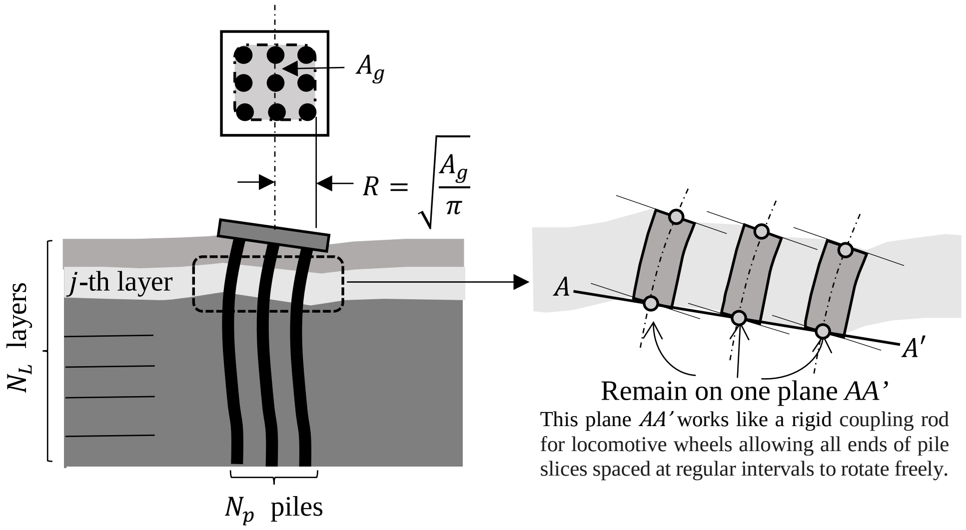


Fig. 2.3 Equivalent single upright beam

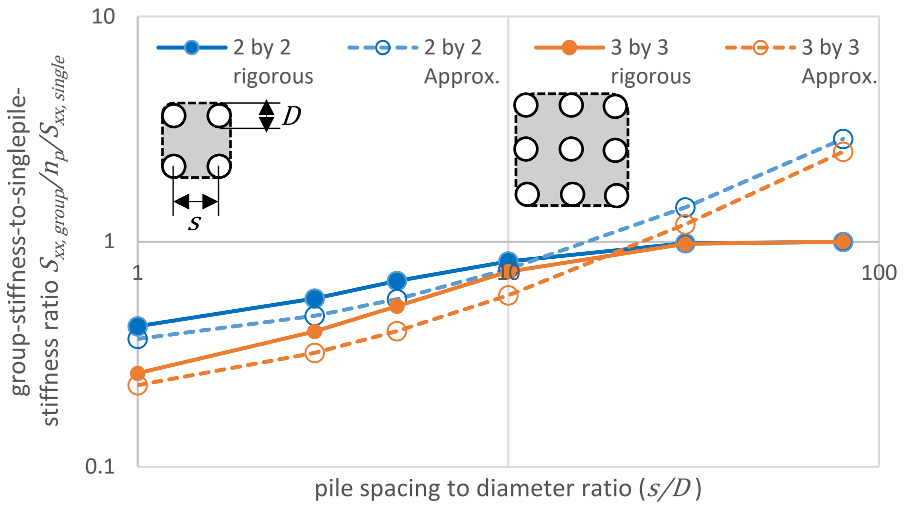


Fig. 2.4 Lateral pile group effects in different pile-to-pile spacing. (Konagai et al, 2003)

To examine the validity of this single-equivalent-upright beam approximation, values of pile cap stiffness in lateral static loading $S_{xx,approx}$ are obtained for different pile groups with different pile-to-pile spacings. Each approximate value of lateral pile cap stiffness $S_{xx,group}$ is then normalized by that for an individual single pile ($S_{xx,single}$) multiplied by the number of piles grouped together beneath a pile cap (n_p):

$$\eta = \frac{S_{xx,group}}{n_p \cdot S_{xx,single}} \tag{2.5}$$

This ratio η, which converges on 1.0 as the pile-to-pile spacing increases, is a measure for describing pile group effect, which values are compared in Fig. 2.4 with their corresponding rigorous solutions. The single equivalent upright beam analogy is found to provide good approximations for the cases of close spacing. As the pile spacing becomes larger, however, the approximation deviates from the rigorous one because piles in the group behave as individual piles rather than behave as what has been assumed in the equivalent beam analogy. See more details in (Konagai et al, 2003).

3. LET’S GET “*TLEM*” STARTED!

TLEM1_2.exe was developed by Kazuo Konagai in 1999 using FORTRAN 77. The original version of TLEM1_2.exe as well as TLEMz.exe for vertical response of piles required a lot of work to prepare necessary input data files using a text editor in strict accordance with fixed formats. Since Microsoft EXCEL has become a standard platform of spreadsheet, an EXCEL Macro, “TLEM1_3.xlsm”, was developed in 2018 to automate all the tasks for preparing data files, running TLEM and showing the results.

Requirements:

TLEM1_3 requires Microsoft EXCEL (preferably Version 14 (EXCEL 2010) or above) installed on your Windows machine.

1st, save the following two EXCEL macros and three executable files on the same folder (**Fig. 3.1**). These files are:

(1) TLEM1_3.xlms
(2) TLEM_Output.xlms
(3) TLEM1_2.exe
(4) TLEMz.exe
(5) PLPRM.exe

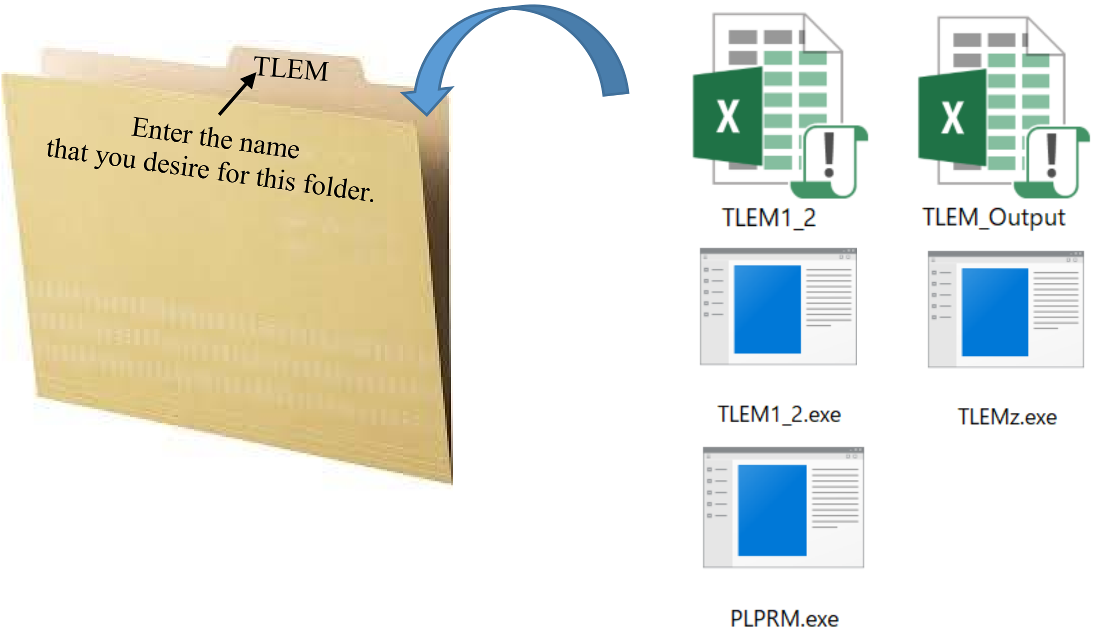
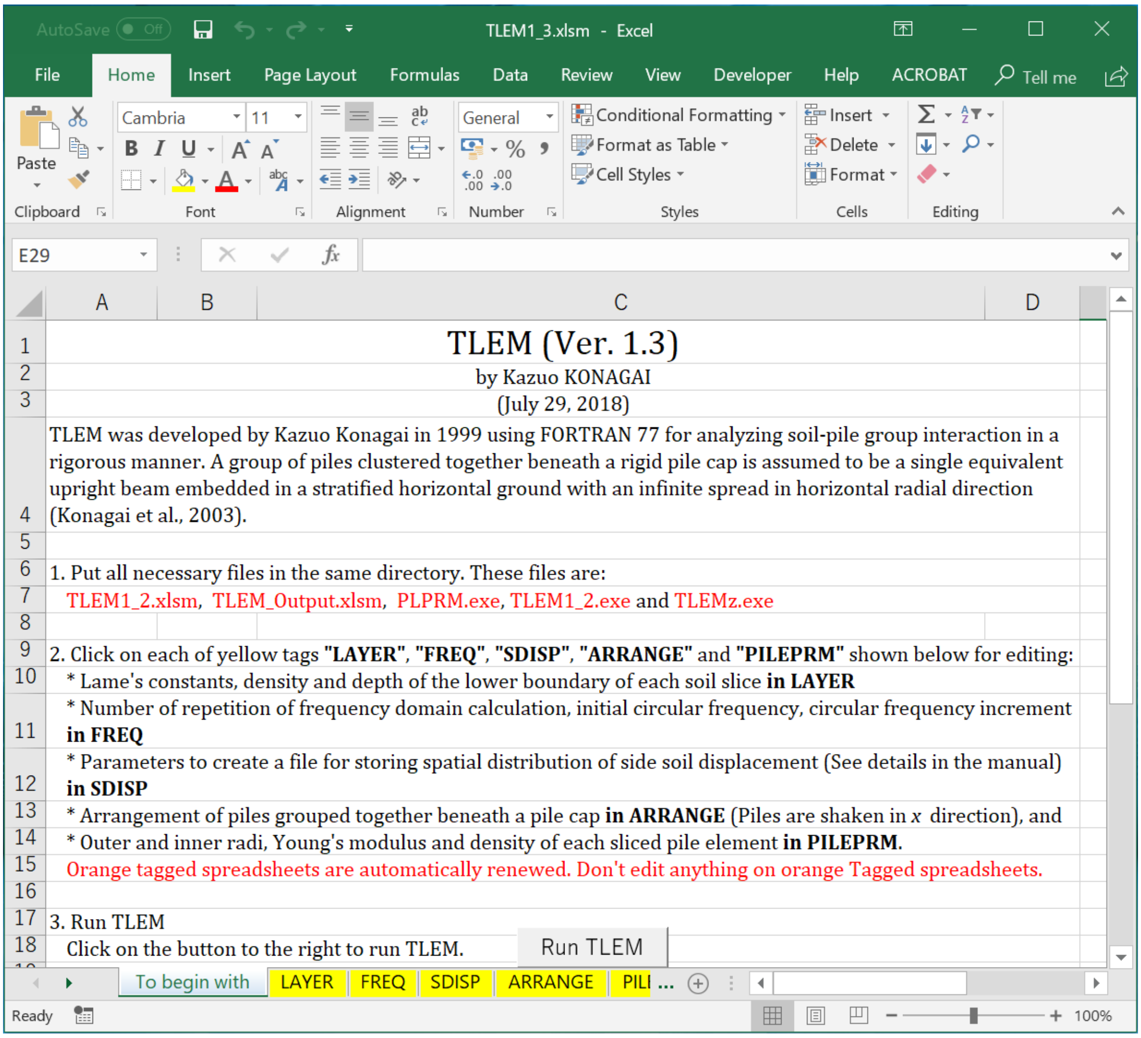


Fig. 3.1 Necessary files for TLEM1_2.

2nd, run TLEM1_3.xlms.

Click “TLEM1_3.xlms”, and the spreadsheet “To begin with” appears (Fig. 3.2).



1 TLEM (Ver. 1.3)
2 by Kazuo KONAGAI
3 (July 29, 2018)
4 TLEM was developed by Kazuo Konagai in 1999 using FORTRAN 77 for analyzing soil-pile group interaction in a rigorous manner. A group of piles clustered together beneath a rigid pile cap is assumed to be a single equivalent upright beam embedded in a stratified horizontal ground with an infinite spread in horizontal radial direction (Konagai et al., 2003).
5
6 1. Put all necessary files in the same directory. These files are:
7 TLEM1_2.xlsm, TLEM_Output.xlsm, PLPRM.exe, TLEM1_2.exe and TLEMz.exe
8
9 2. Click on each of yellow tags **"LAYER"**, **"FREQ"**, **"SDISP"**, **"ARRANGE"** and **"PILEPRM"** shown below for editing:
10 * Lame's constants, density and depth of the lower boundary of each soil slice **in LAYER**
11 * Number of repetition of frequency domain calculation, initial circular frequency, circular frequency increment **in FREQ**
12 * Parameters to create a file for storing spatial distribution of side soil displacement (See details in the manual) **in SDISP**
13 * Arrangement of piles grouped together beneath a pile cap **in ARRANGE** (Piles are shaken in *x* direction), and
14 * Outer and inner radi, Young's modulus and density of each sliced pile element **in PILEPRM**.
15 Orange tagged spreadsheets are automatically renewed. Don't edit anything on orange Tagged spreadsheets.
16
17 3. Run TLEM
18 Click on the button to the right to run TLEM. Run TLEM

Fig. 3.2 Spreadsheet “To begin with”

Five yellow worksheet tabs that appear the bottom of the window are for editing input data of TLEM1_2.

From the 2nd left, they are:

“**LAYER**” for Lame's constants, density and depth of the lower boundary of each soil slice,

“**FREQ**” for number of repetition of frequency domain calculation, initial circular frequency, circular frequency increment,

“**SDISP**” for parameters to create a file for storing spatial distribution of side soil displacement,

“**ARRANGE**” for arrangement of piles grouped together beneath a pile cap, and

"**PILEPRM**" for mechanical properties (outer and inner radii, Young's modulus and density) of each sliced pile element.

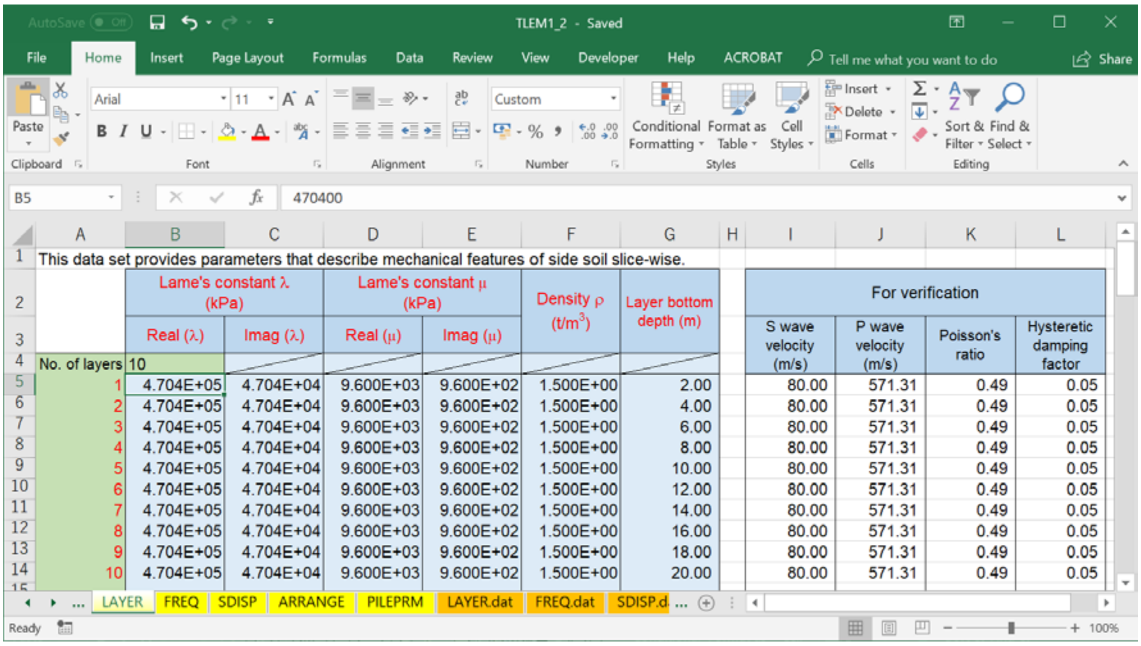
Contents in orange tabbed spreadsheets will be automatically renewed. **Don't edit anything on orange tabbed spreadsheets.**

"**LAYER**"

On this spreadsheet,

(1) Select Cell B4 first and type the number of layers (soil slices). Then the layer numbers are automatically shown in red in an ascending order on the leftmost column A.

(2) This array of layer numbers shows the required range to input the following parameters for side soil slices. From the 2nd left, these parameters are:
Columns B and C: Real and imaginary parts of Lame's constant λ (kPa), respectively,
Columns D and E: Real and imaginary parts of Lame's constant μ (kPa), respectively,
Column F: Density of side soil slice (t/m^3), and
Column G: Depth of each soil slice bottom (m)



B5 470400

	A	B	C	D	E	F	G	H	I	J	K	L
1	This data set provides parameters that describe mechanical features of side soil slice-wise.											
2		Lame's constant λ (kPa)		Lame's constant μ (kPa)		Density ρ (t/m^3)	Layer bottom depth (m)		For verification			
3		Real (λ)	Imag (λ)	Real (μ)	Imag (μ)				S wave velocity (m/s)	P wave velocity (m/s)	Poisson's ratio	Hysteretic damping factor
4	No. of layers	10										
5	1	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	2.00		80.00	571.31	0.49	0.05
6	2	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	4.00		80.00	571.31	0.49	0.05
7	3	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	6.00		80.00	571.31	0.49	0.05
8	4	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	8.00		80.00	571.31	0.49	0.05
9	5	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	10.00		80.00	571.31	0.49	0.05
10	6	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	12.00		80.00	571.31	0.49	0.05
11	7	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	14.00		80.00	571.31	0.49	0.05
12	8	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	16.00		80.00	571.31	0.49	0.05
13	9	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	18.00		80.00	571.31	0.49	0.05
14	10	4.704E+05	4.704E+04	9.600E+03	9.600E+02	1.500E+00	20.00		80.00	571.31	0.49	0.05

Fig. 3.3 Spreadsheet "LAYER"

Automatically, S-wave and P-wave velocities (m/s), Poisson's ratios and hysteretic damping factors for all soil slices are given in the left table for your information.

“**FREQ**”

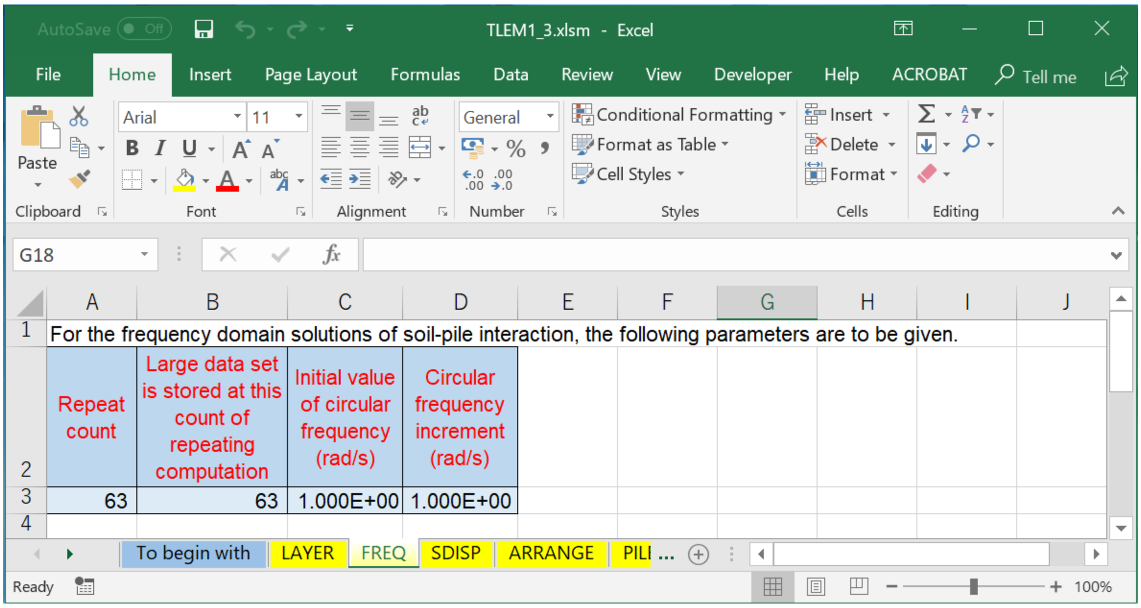
On this spreadsheet, fill up cells from A3 to D3 the followings:

A3: Number of repetition of frequency domain calculation,

B3: At this count of frequency domain calculation, a large data set “space_dsp.dat” of spatial distribution of side soil displacements is created,

C3: Initial value of circular frequency (rad/s), and

D3: Circular frequency increment (rad/s)



For the frequency domain solutions of soil-pile interaction, the following parameters are to be given.

A	B	C	D
Repeat count	Large data set is stored at this count of repeating computation	Initial value of circular frequency (rad/s)	Circular frequency increment (rad/s)
63	63	1.000E+00	1.000E+00

Fig. 3.4 Spreadsheet “FREQ”

“**SDISP**”

A data file “space_dsp.dat” for spatial distribution of side soil displacements is created at a specified count of repeating frequency domain calculation (see B3 on “FREQ”). On this spread sheet (Fig. 3.5 on the next page), fill up cells from A4 to E4 the followings:

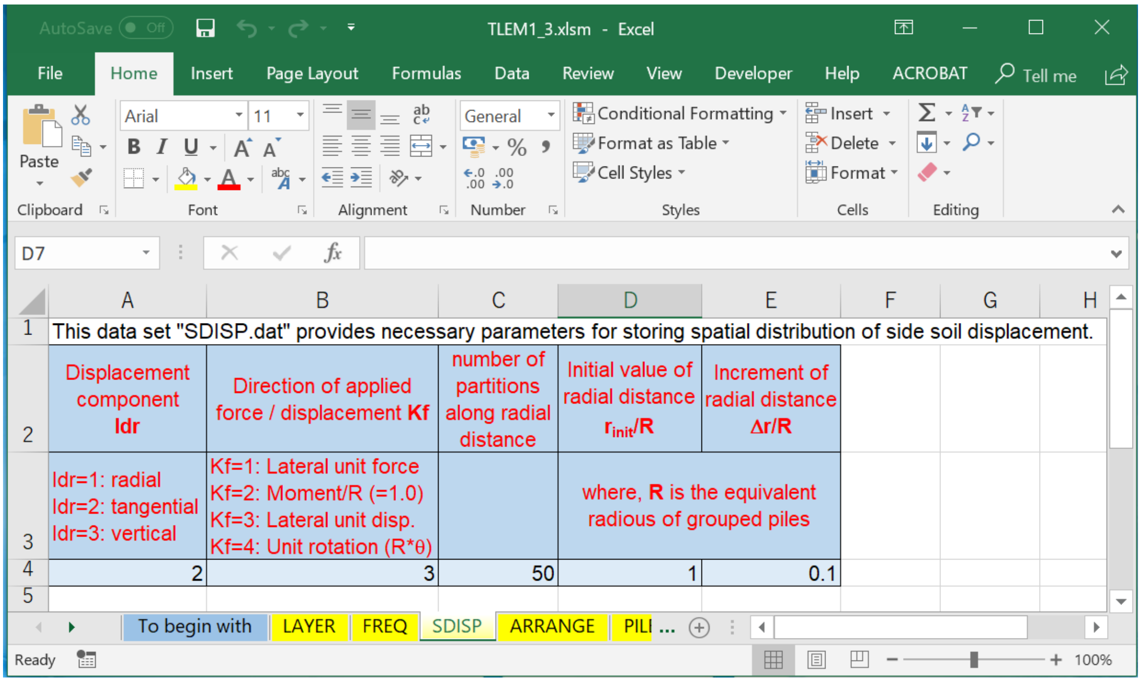
A4: Index I_{dr} to specify which displacement component will be saved (I_{dr} =1, 2 and 3 for radial, tangential and vertical, respectively),

B4: Index K_f to specify which unit force / unit displacement will be applied to the pile cap (K_f =1, 2, 3 and 4 for lateral unit force, unit M_y/R, lateral unit displacement and unit $R \cdot \theta_y^r$, respectively),

C4: Number of partitions along radial distance (rad/s) for 3D plot of soil displacement,

D4: Initial value of radial distance normalized by R, r_{init}/R, and

E4: Increment of normalized radial distance $\Delta r/R$



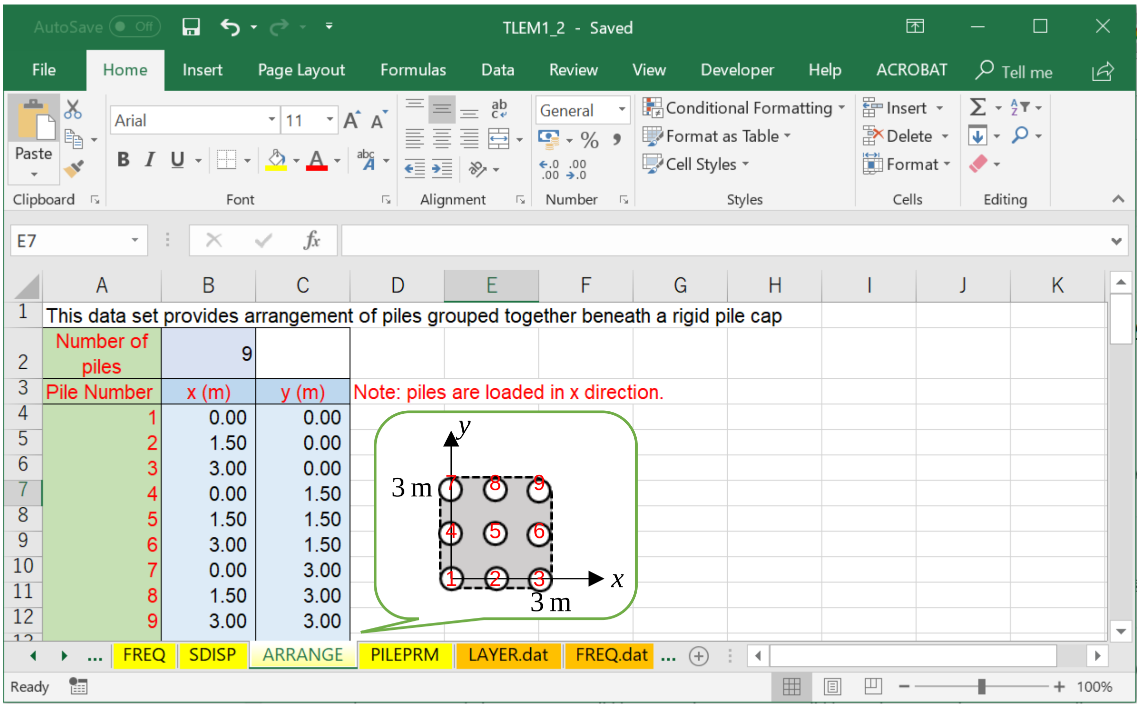
This data set "SDISP.dat" provides necessary parameters for storing spatial distribution of side soil displacement.

Displacement component **Idr**	Direction of applied force / displacement **Kf**	number of partitions along radial distance	Initial value of radial distance r_{init}/R	Increment of radial distance $\Delta r/R$
Idr=1: radial Idr=2: tangential Idr=3: vertical	Kf=1: Lateral unit force Kf=2: Moment/R (=1.0) Kf=3: Lateral unit disp. Kf=4: Unit rotation (R*θ)		where, **R** is the equivalent radious of grouped piles	
2	3	50	1	0.1

Fig. 3.5 Spreadsheet "SDISP"

"**ARRANGE**"

First, type the number of piles grouped beneath a pile cap, and pile numbers will be shown in red on the leftmost column A. Then fill up columns B and C with *x* and *y* coordinate values for these piles. Note piles are shaken in *x* direction.



This data set provides arrangement of piles grouped together beneath a rigid pile cap

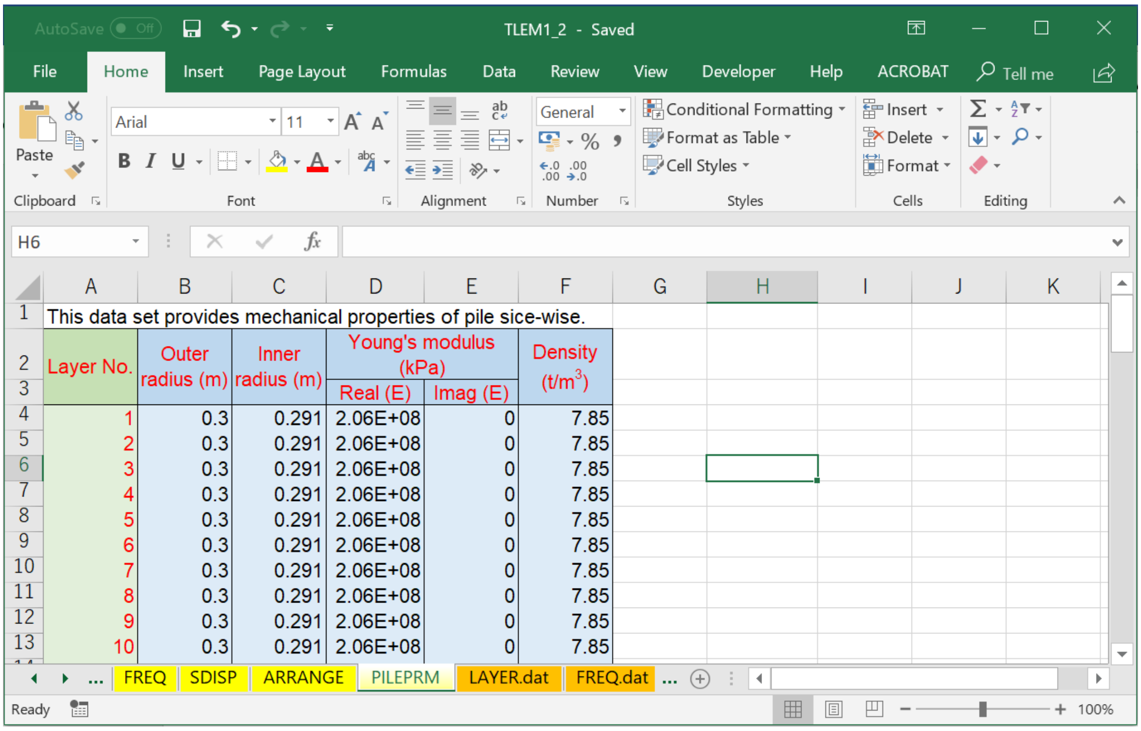
Number of piles	9	
Pile Number	x (m)	y (m)
1	0.00	0.00
2	1.50	0.00
3	3.00	0.00
4	0.00	1.50
5	1.50	1.50
6	3.00	1.50
7	0.00	3.00
8	1.50	3.00
9	3.00	3.00

Note: piles are loaded in x direction.

Fig. 3.6 Spreadsheet "ARRANGE"

“**PILEPRM**”

This spread sheet is for editing the following mechanical properties of piles embedded in each soil slice:
Column A: Layer numbers are shown automatically.
Columns B and C: Outer and inner radii of sliced piles,
Columns D and E: Real and imaginary parts of Young's moduli of sliced piles, and
Column F: Densities of sliced piles
For friction piles, mechanical properties for slices below the pile ends can be replaced with those for soils.



This data set provides mechanical properties of pile sice-wise.

Layer No.	Outer radius (m)	Inner radius (m)	Young's modulus (kPa) Real (E)	Young's modulus (kPa) Imag (E)	Density (t/m^3)
1	0.3	0.291	2.06E+08	0	7.85
2	0.3	0.291	2.06E+08	0	7.85
3	0.3	0.291	2.06E+08	0	7.85
4	0.3	0.291	2.06E+08	0	7.85
5	0.3	0.291	2.06E+08	0	7.85
6	0.3	0.291	2.06E+08	0	7.85
7	0.3	0.291	2.06E+08	0	7.85
8	0.3	0.291	2.06E+08	0	7.85
9	0.3	0.291	2.06E+08	0	7.85
10	0.3	0.291	2.06E+08	0	7.85

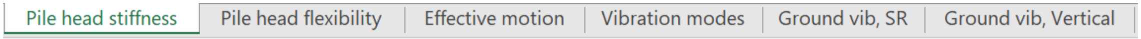
Fig. 3.7 Spreadsheet “PILEPRM”

After you finish editing all yellow tabbed spreadsheets, go back to the leftmost startup spreadsheet “To begin with” (Fig. 3.2), and click on Run TLEM to start TLEM1_2.exe and TLEMz.exe.

Calculation will over in a moment, and “TLEM_Output.xlms” will open automatically. Numerical results will be shown on its 6 spreadsheets (see the following pages).

3$^{\text{rd}}$, check out your results on TLEM_Output.xlms.

TLEM_Output.xlms has 6 spreadsheets. They are:



“Pile head stiffness”

Four figures appear on this spreadsheet. From left to right and continuing down, they are;

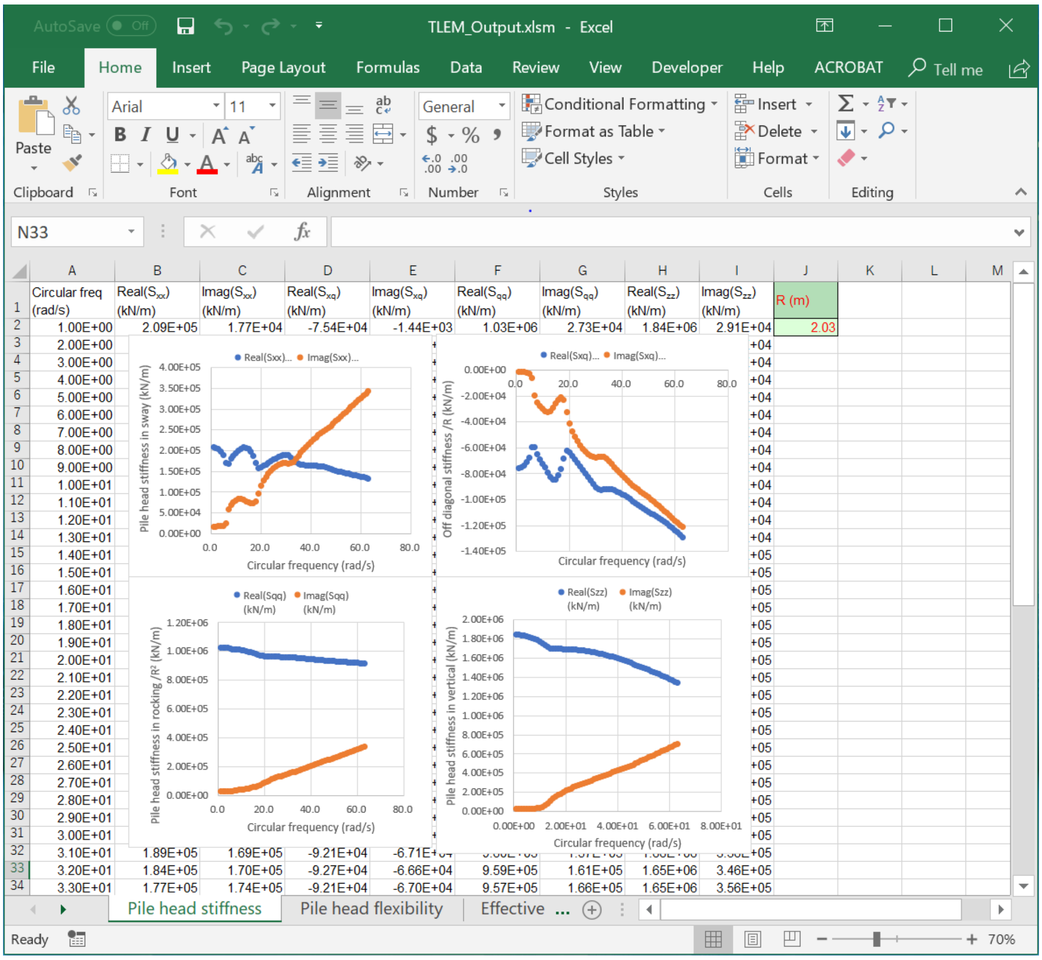
(1) Real and imaginary parts of the stiffness for sway motion u_x^r of the pile cap S_{xx},

(2) Real and imaginary parts of the off-diagonal pile cap stiffness S_{xq} (to describe transferring effect from q to x); Note that $S_{xq} = S_{qx}$ and

(3) Real and imaginary parts of the stiffness, S_{qq}. See in **Fig. 2.2** and in Equation (3.1) the relation between the pile cap rotation θ_y^r and the displacement u_q^r at the outermost edge of the equivalent upright beam.

(4) Real and imaginary parts of the stiffness for vertical motion u_z^r of the pile cap, S_{zz}

$$\begin{Bmatrix} p_x \\ p_q(=M_y/R) \\ p_z \end{Bmatrix} = \begin{bmatrix} S_{xx} & S_{xq} & 0 \\ S_{qx} & S_{qq} & 0 \\ 0 & 0 & S_{zz} \end{bmatrix} \begin{Bmatrix} u_x^r \\ u_q^r(=R\theta_y^r) \\ u_z^r \end{Bmatrix} \tag{3.1}$$



	A	B	C	D	E	F	G	H	I	J
1	Circular freq (rad/s)	Real(S_{xx}) (kN/m)	Imag(S_{xx}) (kN/m)	Real(S_{xq}) (kN/m)	Imag(S_{xq}) (kN/m)	Real(S_{qq}) (kN/m)	Imag(S_{qq}) (kN/m)	Real(S_{zz}) (kN/m)	Imag(S_{zz}) (kN/m)	R (m)
2	1.00E+00	2.09E+05	1.77E+04	-7.54E+04	-1.44E+03	1.03E+06	2.73E+04	1.84E+06	2.91E+04	2.03
3	2.00E+00								+04	
4	3.00E+00								+04	
5	4.00E+00								+04	
6	5.00E+00								+04	
7	6.00E+00								+04	
8	7.00E+00								+04	
9	8.00E+00								+04	
10	9.00E+00								+04	
11	1.00E+01								+04	
12	1.10E+01								+04	
13	1.20E+01								+04	
14	1.30E+01								+04	
15	1.40E+01								+05	
16	1.50E+01								+05	
17	1.60E+01								+05	
18	1.70E+01								+05	
19	1.80E+01								+05	
20	1.90E+01								+05	
21	2.00E+01								+05	
22	2.10E+01								+05	
23	2.20E+01								+05	
24	2.30E+01								+05	
25	2.40E+01								+05	
26	2.50E+01								+05	
27	2.60E+01								+05	
28	2.70E+01								+05	
29	2.80E+01								+05	
30	2.90E+01								+05	
31	3.00E+01								+05	
32	3.10E+01	1.89E+05	1.69E+05	-9.21E+04	-6.71E+				+05	
33	3.20E+01	1.84E+05	1.70E+05	-9.27E+04	-6.66E+04	9.59E+05	1.61E+05	1.65E+06	3.46E+05	
34	3.30E+01	1.77E+05	1.74E+05	-9.21E+04	-6.70E+04	9.57E+05	1.66E+05	1.65E+06	3.56E+05	

Fig. 3.8 Spreadsheet “Pile head stiffness” in TLEM_Output.xlms

The idea about complex stiffness with its real and imaginary parts may be unfamiliar to some of you, and the illustration below in Fig. 3.9 will probably help you to understand it.

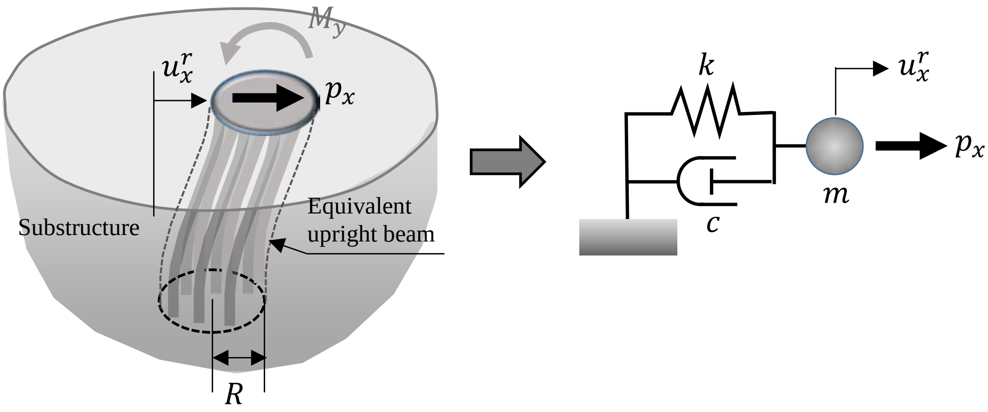


Fig. 3.9 Super and sub-structures to analyze

When a lateral dynamic load p_x is applied to the pile cap not allowing the cap to rotate, you need to apply a counter-clockwise moment M_y to the cap. These loads are given by:

$$p_x = S_{xx} u_x^r \tag{3.2a}$$

$$M_y / R = S_{qx} u_x^r \tag{3.2b}$$

For simplicity however, only equation (3.2a) is discussed in the frequency domain. The stiffness of the pile cap in its sway motion can be approximated as a parallel assemblage of a spring *k* and a damper *c* with a mass *m* attached on its end (Fig. 3.8). The motion of this simple mechanical model is given by:

$$p_x = m \frac{d^2 u_x^r}{dt^2} + c \frac{d u_x^r}{dt} + k u_x^r \tag{3.3}$$

In the frequency domain, p_x and u_x^r are given by:

$$p_x = P_x e^{i\omega t} \tag{3.4a}$$

$$u_x^r = U_x^r e^{i\omega t} \tag{3.4b}$$

Substituting equations (3.4a) and (3.4b), one obtains:

$$\frac{p_x}{u_x^r} = S_{xx} = (k - m\omega^2) + i\omega c \tag{3.5}$$

It is now clear that S_{xx} has its real part $k - m\omega^2$, which is a gently decreasing parabola with increasing ω^2 and imaginary part ωc, which increases linearly with increasing ω. Thus, the simple mechanical model in Fig. 3.8 is a good analogy of the frequency domain nature of S_{xx} that can be seen on the upper-left figure on the spreadsheet “pile head stiffness”, though there are some downward spikes on the curves, which spikes appear when the side soil is brought into resonance.

Note that real part of S_{qx} begins with a negative value indicating that when the rotation of a pile cap is not allowed, positive sway motion of the pile cap can exert a negative counter-clockwise moment as shown in **Fig. 3.8**.

"Pile head flexibility"

Four figures appear on this spreadsheet. From left to right and continuing down, they are;

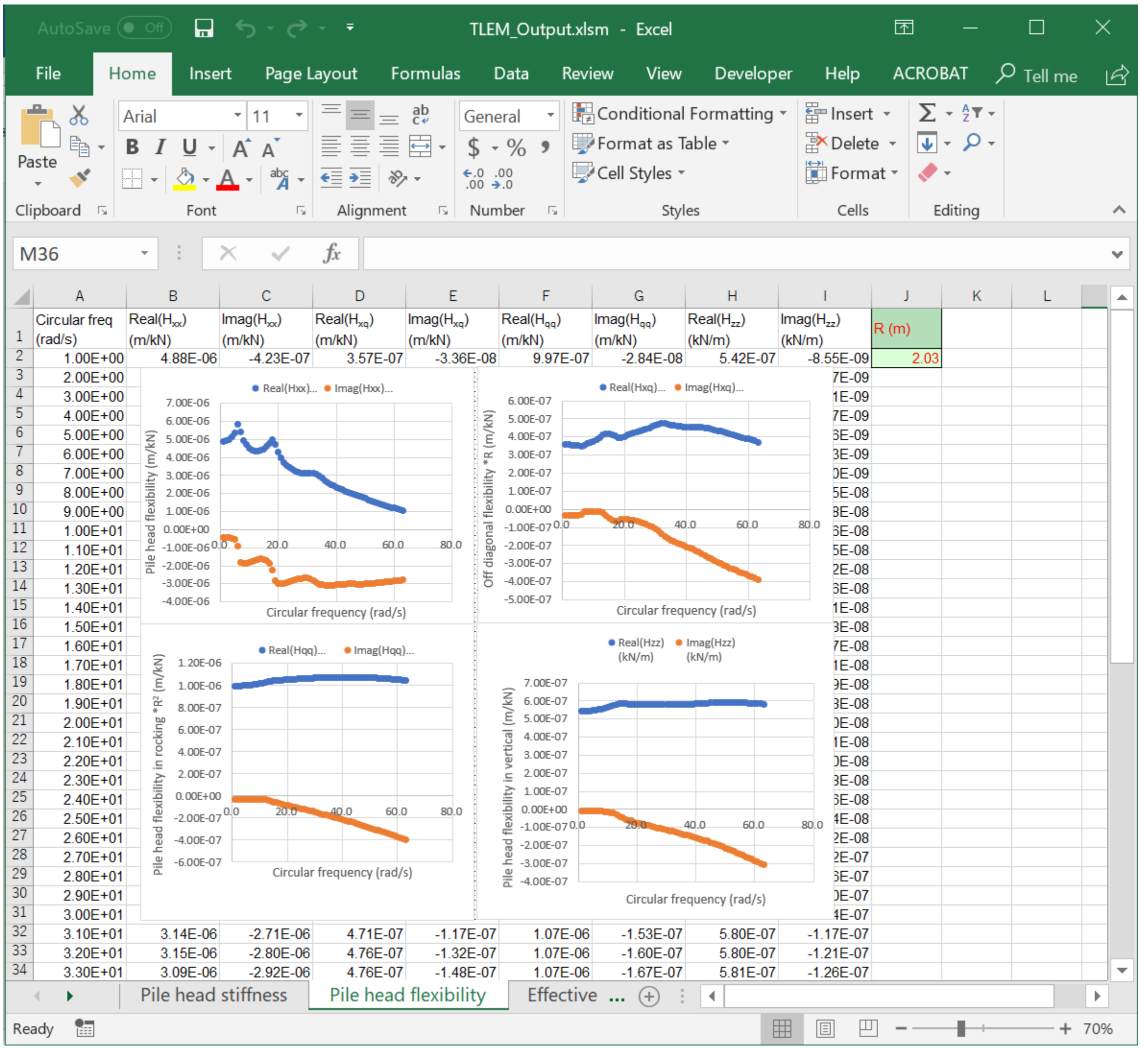
(1) Real and imaginary parts of the flexibility for lateral loading p_x to the pile cap H_{xx},

(2) Real and imaginary parts of the off-diagonal pile cap flexibility (to describe transferring effect from q to x), H_{xq}; Note that $H_{xq} = H_{qx}$,

(3) Real and imaginary parts of the flexibility for $p_q (= M_y/R)$, H_{qq}. See equation (3.6) below, and

(4) Real and imaginary parts of the flexibility for vertical loading p_z, H_{zz}.

$$\begin{Bmatrix} u_x^r \\ u_q^r (= R\theta_y^r) \\ u_z^r \end{Bmatrix} = \begin{bmatrix} H_{xx} & H_{xq} & 0 \\ H_{qx} & H_{qq} & 0 \\ 0 & 0 & H_{zz} \end{bmatrix} \begin{Bmatrix} p_x \\ p_q (= M_y/R) \\ p_z \end{Bmatrix} \tag{3.6}$$



Circular freq (rad/s)	Real(H_{xx}) (m/kN)	Imag(H_{xx}) (m/kN)	Real(H_{xq}) (m/kN)	Imag(H_{xq}) (m/kN)	Real(H_{qq}) (m/kN)	Imag(H_{qq}) (m/kN)	Real(H_{zz}) (kN/m)	Imag(H_{zz}) (kN/m)	R (m)
1.00E+00	4.88E-06	-4.23E-07	3.57E-07	-3.36E-08	9.97E-07	-2.84E-08	5.42E-07	-8.55E-09	2.03
2.00E+00									
3.00E+00									
4.00E+00									
5.00E+00									
6.00E+00									
7.00E+00									
8.00E+00									
9.00E+00									
1.00E+01									
1.10E+01									
1.20E+01									
1.30E+01									
1.40E+01									
1.50E+01									
1.60E+01									
1.70E+01									
1.80E+01									
1.90E+01									
2.00E+01									
2.10E+01									
2.20E+01									
2.30E+01									
2.40E+01									
2.50E+01									
2.60E+01									
2.70E+01									
2.80E+01									
2.90E+01									
3.00E+01									
3.10E+01	3.14E-06	-2.71E-06	4.71E-07	-1.17E-07	1.07E-06	-1.53E-07	5.80E-07	-1.17E-07	
3.20E+01	3.15E-06	-2.80E-06	4.76E-07	-1.32E-07	1.07E-06	-1.60E-07	5.80E-07	-1.21E-07	
3.30E+01	3.09E-06	-2.92E-06	4.76E-07	-1.48E-07	1.07E-06	-1.67E-07	5.81E-07	-1.26E-07	

Fig. 3.10 Spreadsheet "Pile head flexibility"

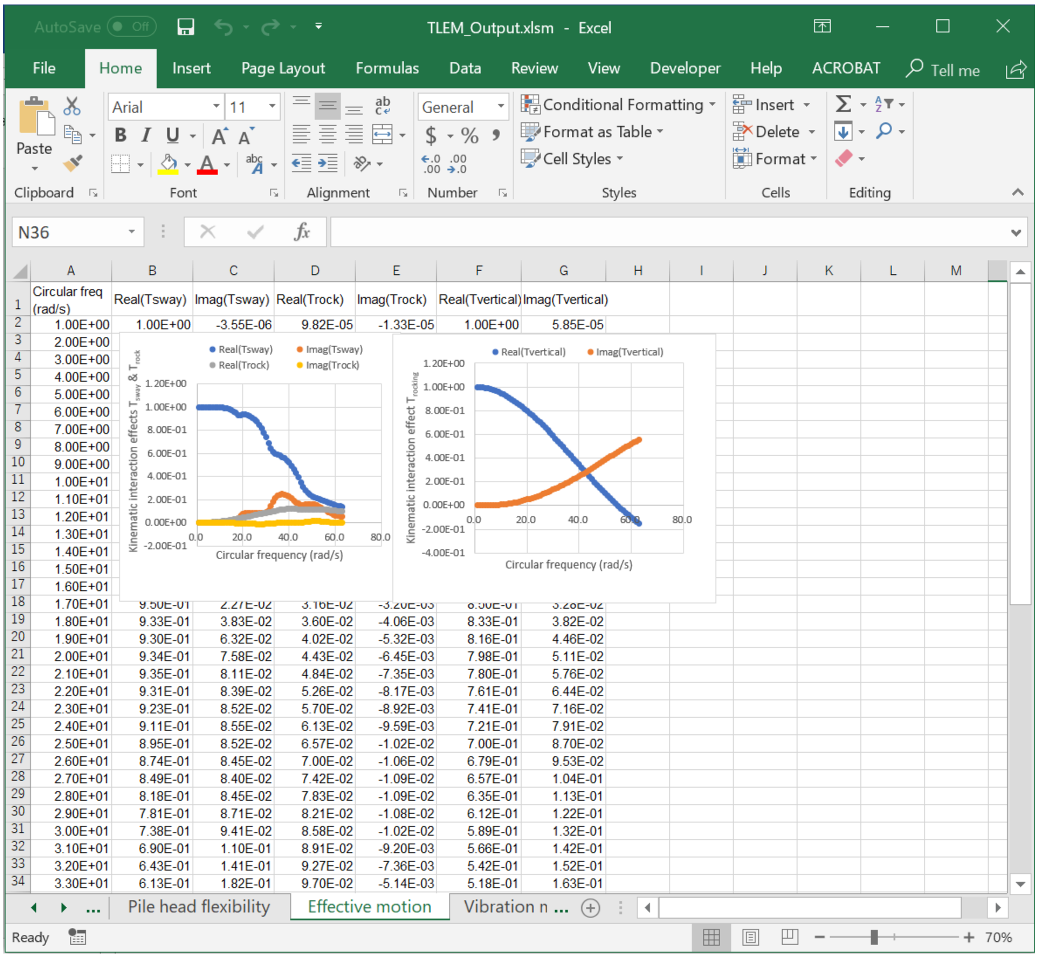
“Effective motion”

Two figures that appear on this spreadsheet show real and imaginary parts of both $T_{e,sway}$, $T_{e,rocking}$ on the left, and $T_{e,vertical}$ on the right, transfer rates of free-field ground motion to grouped pile foundation evaluated at the ground surface level, namely:

$$T_{e,sway} = \left(\frac{u_x^f + u_x^s}{u_x^f}\right)_{top} \qquad (2.4a, \text{as referred on page 3 })$$

$$T_{e,rocking} = \left(\frac{u_q^s}{u_x^f}\right)_{top} \qquad (2.4b, \text{as referred on page 3})$$

$$T_{e,vertical} = \left(\frac{u_z^f + u_z^s}{u_z^f}\right)_{top} \qquad (2.4c, \text{as referred on page 3})$$



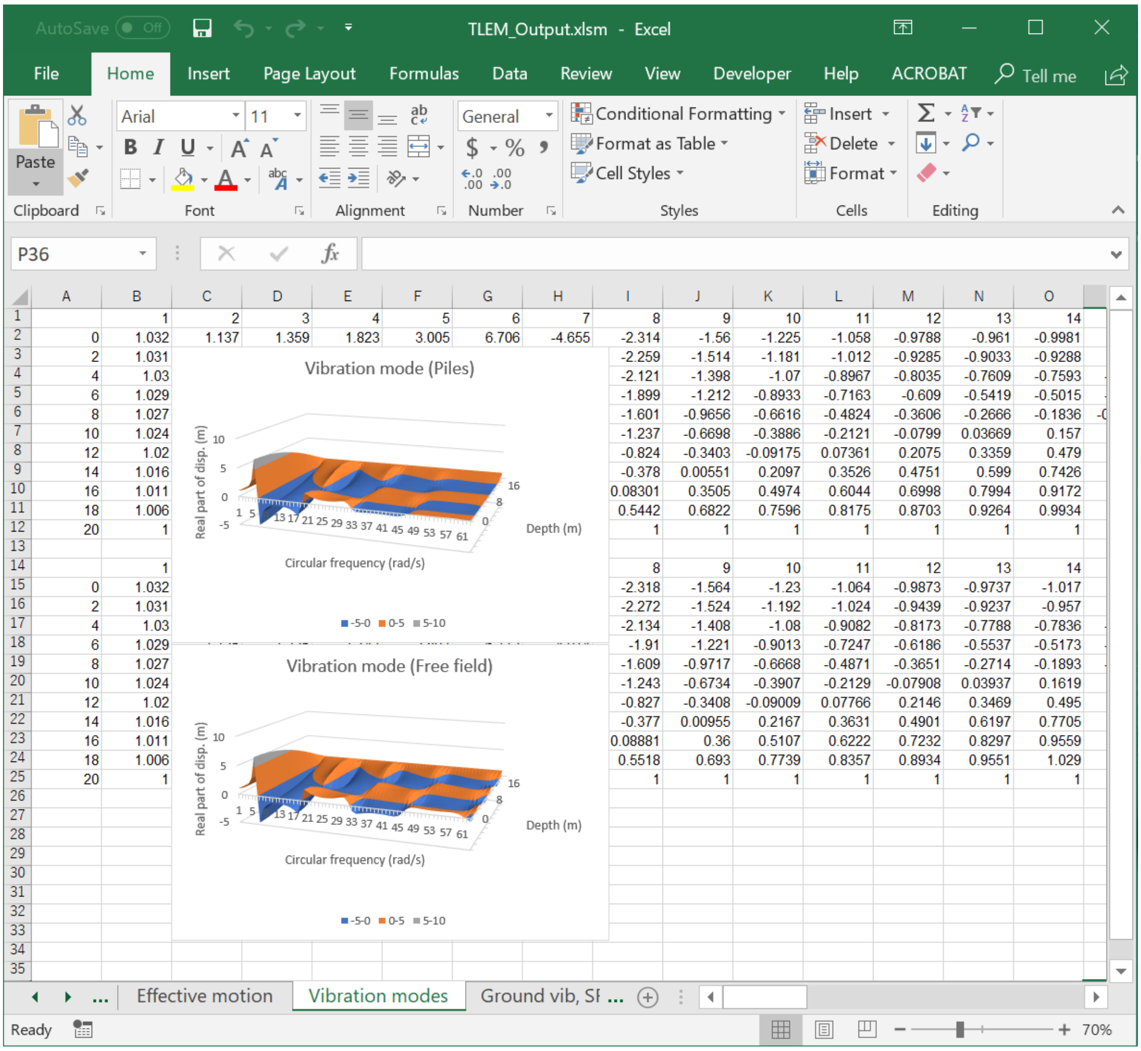
	A	B	C	D	E	F	G
1	Circular freq (rad/s)	Real(Tsway)	Imag(Tsway)	Real(Trock)	Imag(Trock)	Real(Tvertical)	Imag(Tvertical)
2	1.00E+00	1.00E+00	-3.55E-06	9.82E-05	-1.33E-05	1.00E+00	5.85E-05
3	2.00E+00						
4	3.00E+00						
5	4.00E+00						
6	5.00E+00						
7	6.00E+00						
8	7.00E+00						
9	8.00E+00						
10	9.00E+00						
11	1.00E+01						
12	1.10E+01						
13	1.20E+01						
14	1.30E+01						
15	1.40E+01						
16	1.50E+01						
17	1.60E+01						
18	1.70E+01	9.50E-01	2.27E-02	3.16E-02	-3.20E-03	8.50E-01	3.28E-02
19	1.80E+01	9.33E-01	3.83E-02	3.60E-02	-4.06E-03	8.33E-01	3.82E-02
20	1.90E+01	9.30E-01	6.32E-02	4.02E-02	-5.32E-03	8.16E-01	4.46E-02
21	2.00E+01	9.34E-01	7.58E-02	4.43E-02	-6.45E-03	7.98E-01	5.11E-02
22	2.10E+01	9.35E-01	8.11E-02	4.84E-02	-7.35E-03	7.80E-01	5.76E-02
23	2.20E+01	9.31E-01	8.39E-02	5.26E-02	-8.17E-03	7.61E-01	6.44E-02
24	2.30E+01	9.23E-01	8.52E-02	5.70E-02	-8.92E-03	7.41E-01	7.16E-02
25	2.40E+01	9.11E-01	8.55E-02	6.13E-02	-9.59E-03	7.21E-01	7.91E-02
26	2.50E+01	8.95E-01	8.52E-02	6.57E-02	-1.02E-02	7.00E-01	8.70E-02
27	2.60E+01	8.74E-01	8.45E-02	7.00E-02	-1.06E-02	6.79E-01	9.53E-02
28	2.70E+01	8.49E-01	8.40E-02	7.42E-02	-1.09E-02	6.57E-01	1.04E-01
29	2.80E+01	8.18E-01	8.45E-02	7.83E-02	-1.09E-02	6.35E-01	1.13E-01
30	2.90E+01	7.81E-01	8.71E-02	8.21E-02	-1.08E-02	6.12E-01	1.22E-01
31	3.00E+01	7.38E-01	9.41E-02	8.58E-02	-1.02E-02	5.89E-01	1.32E-01
32	3.10E+01	6.90E-01	1.10E-01	8.91E-02	-9.20E-03	5.66E-01	1.42E-01
33	3.20E+01	6.43E-01	1.41E-01	9.27E-02	-7.36E-03	5.42E-01	1.52E-01
34	3.30E+01	6.13E-01	1.82E-01	9.70E-02	-5.14E-03	5.18E-01	1.63E-01

Fig. 3.11 Spreadsheet “Effective motion”

It is noted that the real part of $T_{e,sway}$ decreases gradually from 1.0 to smaller values as the frequency increases indicating that piles start not to follow the incoming free field ground motion as the frequency increases. On the other hand, $T_{e,rocking}$ starts to increase from zero showing that the sole horizontal incoming ground motion can cause rotational motion of the pile cap.

“Vibration modes”

As mentioned above, the seismic incoming motion can be changed along grouped piles, and this kinematic interaction effect can be examined in a more specific manner by comparing two figures that appear on this spreadsheet (Fig. 3.12). The lower figure shows the incoming ground motions along the pile axes in the frequency domain, while the upper figure shows the response of the piles to the incoming ground motion.

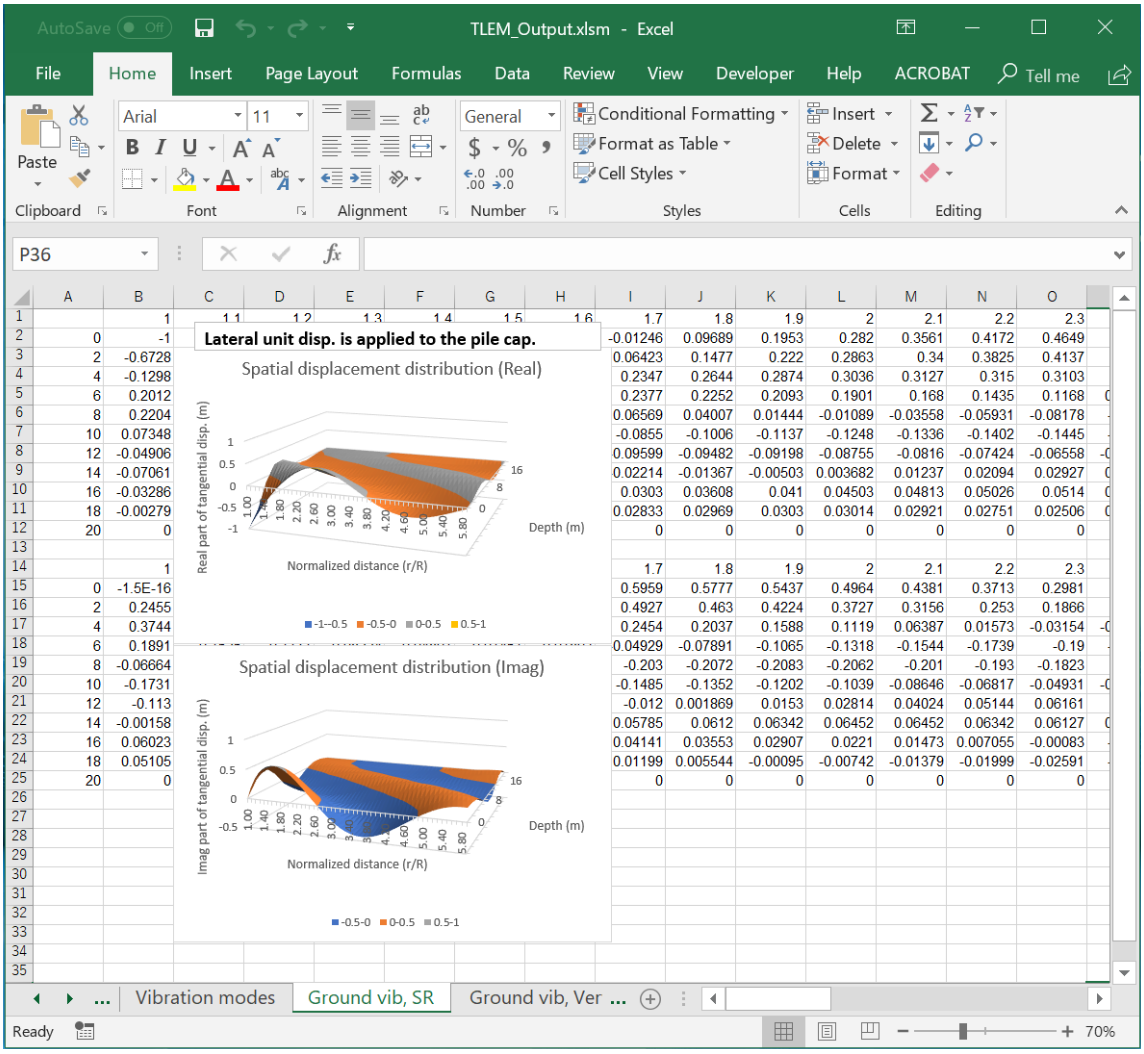


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1		1	2	3	4	5	6	7	8	9	10	11	12	13	14
2	0	1.032	1.137	1.359	1.823	3.005	6.706	-4.655	-2.314	-1.56	-1.225	-1.058	-0.9788	-0.961	-0.9981
3	2	1.031							-2.259	-1.514	-1.181	-1.012	-0.9285	-0.9033	-0.9288
4	4	1.03							-2.121	-1.398	-1.07	-0.8967	-0.8035	-0.7609	-0.7593
5	6	1.029							-1.899	-1.212	-0.8933	-0.7163	-0.609	-0.5419	-0.5015
6	8	1.027							-1.601	-0.9656	-0.6616	-0.4824	-0.3606	-0.2666	-0.1836
7	10	1.024							-1.237	-0.6698	-0.3886	-0.2121	-0.0799	0.03669	0.157
8	12	1.02							-0.824	-0.3403	-0.09175	0.07361	0.2075	0.3359	0.479
9	14	1.016							-0.378	0.00551	0.2097	0.3526	0.4751	0.599	0.7426
10	16	1.011							0.08301	0.3505	0.4974	0.6044	0.6998	0.7994	0.9172
11	18	1.006							0.5442	0.6822	0.7596	0.8175	0.8703	0.9264	0.9934
12	20	1							1	1	1	1	1	1	1
13															
14		1							8	9	10	11	12	13	14
15	0	1.032							-2.318	-1.564	-1.23	-1.064	-0.9873	-0.9737	-1.017
16	2	1.031							-2.272	-1.524	-1.192	-1.024	-0.9439	-0.9237	-0.957
17	4	1.03							-2.134	-1.408	-1.08	-0.9082	-0.8173	-0.7788	-0.7836
18	6	1.029							-1.91	-1.221	-0.9013	-0.7247	-0.6186	-0.5537	-0.5173
19	8	1.027							-1.609	-0.9717	-0.6668	-0.4871	-0.3651	-0.2714	-0.1893
20	10	1.024							-1.243	-0.6734	-0.3907	-0.2129	-0.07908	0.03937	0.1619
21	12	1.02							-0.827	-0.3408	-0.09009	0.07766	0.2146	0.3469	0.495
22	14	1.016							-0.377	0.00955	0.2167	0.3631	0.4901	0.6197	0.7705
23	16	1.011							0.08881	0.36	0.5107	0.6222	0.7232	0.8297	0.9559
24	18	1.006							0.5518	0.693	0.7739	0.8357	0.8934	0.9551	1.029
25	20	1							1	1	1	1	1	1	1
26															
27															
28															
29															
30															
31															
32															
33															
34															
35															

Fig. 3.12 Spreadsheet “Vibration modes”

“Ground Vib, SR”

Real and imaginary parts of either radial or tangential ground displacement caused by a unit sinusoidal pile-cap loading are shown in upper and lower figures on this spread sheet, respectively. Each of these 3D images is a snapshot, with the lateral axis r/R as the radial distance r normalized by R, the depth axis as the depth of the ground and the vertical axis as ether real or imaginary part of ground displacement, at a particular count of repeating frequency-domain calculation, which count is given in advance in Cell “B3” on the spreadsheet “FREQ” of TLEM1_3.xlms. The displacement component is specified in advance by an integer parameter I_{dr} in Cell “A4” on the spreadsheet “SDISP” of TLEM1_3.xlms. The direction of applied load/ displacement is also specified by another integer parameter K_f in Cell “B4” on the same spreadsheet (See more details on page 8 to 9). The direction (type) of loading is automatically shown in the text box near the top of this spreadsheet “Ground Vib, SR” (Fig. 3.13).



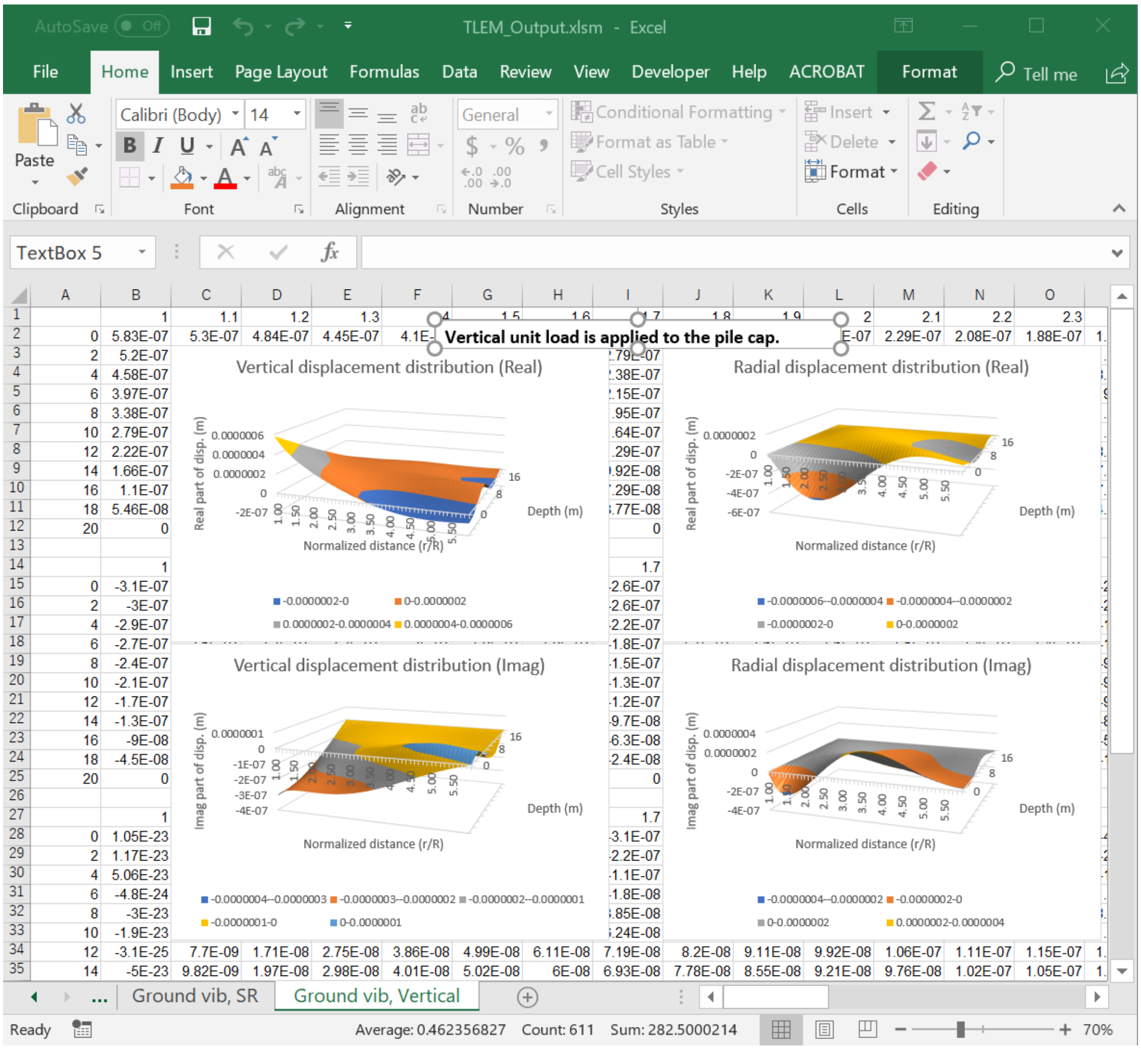
Lateral unit disp. is applied to the pile cap.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1		1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3
2	0	-1							-0.01246	0.09689	0.1953	0.282	0.3561	0.4172	0.4649
3	2	-0.6728							0.06423	0.1477	0.222	0.2863	0.34	0.3825	0.4137
4	4	-0.1298							0.2347	0.2644	0.2874	0.3036	0.3127	0.315	0.3103
5	6	0.2012							0.2377	0.2252	0.2093	0.1901	0.168	0.1435	0.1168
6	8	0.2204							0.06569	0.04007	0.01444	-0.01089	-0.03558	-0.05931	-0.08178
7	10	0.07348							-0.0855	-0.1006	-0.1137	-0.1248	-0.1336	-0.1402	-0.1445
8	12	-0.04906							0.09599	-0.09482	-0.09198	-0.08755	-0.0816	-0.07424	-0.06558
9	14	-0.07061							0.02214	-0.01367	-0.00503	0.003682	0.01237	0.02094	0.02927
10	16	-0.03286							0.0303	0.03608	0.041	0.04503	0.04813	0.05026	0.0514
11	18	-0.00279							0.02833	0.02969	0.0303	0.03014	0.02921	0.02751	0.02506
12	20	0							0	0	0	0	0	0	0
13															
14		1							1.7	1.8	1.9	2	2.1	2.2	2.3
15	0	-1.5E-16							0.5959	0.5777	0.5437	0.4964	0.4381	0.3713	0.2981
16	2	0.2455							0.4927	0.463	0.4224	0.3727	0.3156	0.253	0.1866
17	4	0.3744							0.2454	0.2037	0.1588	0.1119	0.06387	0.01573	-0.03154
18	6	0.1891							0.04929	-0.07891	-0.1065	-0.1318	-0.1544	-0.1739	-0.19
19	8	-0.06664							-0.203	-0.2072	-0.2083	-0.2062	-0.201	-0.193	-0.1823
20	10	-0.1731							-0.1485	-0.1352	-0.1202	-0.1039	-0.08646	-0.06817	-0.04931
21	12	-0.113							-0.012	0.001869	0.0153	0.02814	0.04024	0.05144	0.06161
22	14	-0.00158							0.05785	0.0612	0.06342	0.06452	0.06452	0.06342	0.06127
23	16	0.06023							0.04141	0.03553	0.02907	0.0221	0.01473	0.007055	-0.00083
24	18	0.05105							0.01199	0.005544	-0.00095	-0.00742	-0.01379	-0.01999	-0.02591
25	20	0							0	0	0	0	0	0	0

Fig. 3.13 Spreadsheet “Ground Vib, SR”

“Ground Vib, Vertical”

Real and imaginary parts of both vertical (left two figures) and radial (right two figures) ground displacements caused by a unit vertical pile-cap loading are shown on this spread sheet “Ground Vib, Vertical”. Each of these 3D images is a snapshot, with the lateral axis r/R as the radial distance r normalized by R, the depth axis as the depth of the ground and the vertical axis as ether real or imaginary part of ground displacements, at a particular count of repeating frequency-domain calculation, which count is given in advance in Cell “B3” on the spreadsheet “FREQ” of TLEM1_3.xlms.



Vertical unit load is applied to the pile cap.

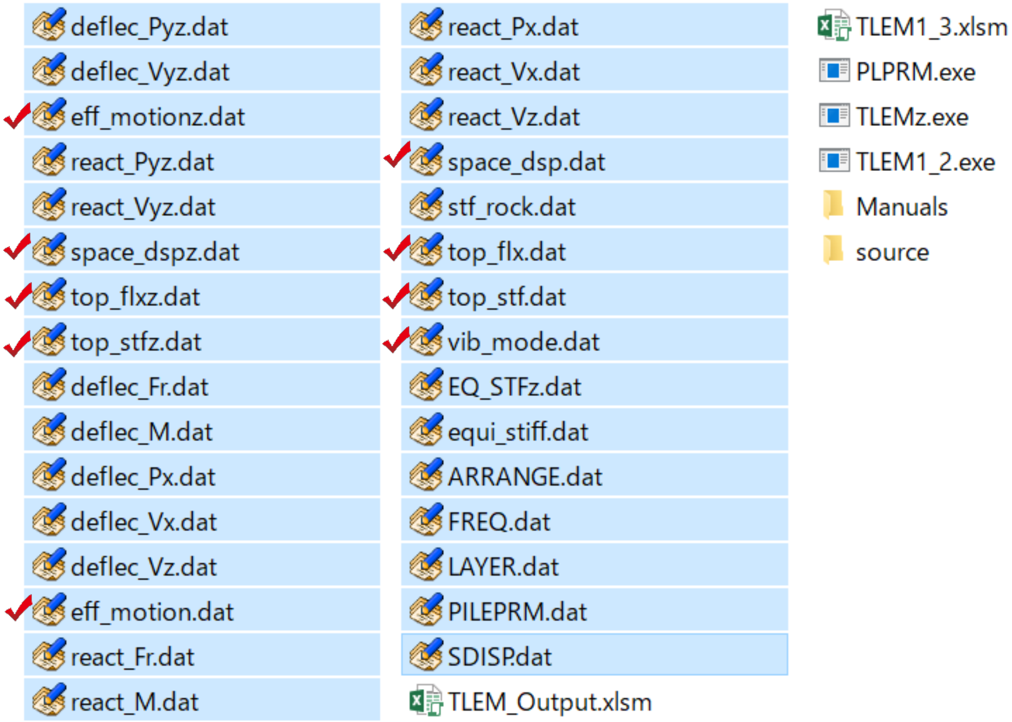
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	
1		1	1.1	1.2	1.3	4	1.5	1.6	1.7	1.8	1.9	2	2.1	2.2	2.3	
2	0	5.83E-07	5.3E-07	4.84E-07	4.45E-07	4.1E-						E-07	2.29E-07	2.08E-07	1.88E-07	1.
3	2	5.2E-07							.79E-07							
4	4	4.58E-07							.38E-07							
5	6	3.97E-07							.15E-07							
6	8	3.38E-07							.95E-07							
7	10	2.79E-07							.64E-07							
8	12	2.22E-07							.29E-07							
9	14	1.66E-07							.92E-08							
10	16	1.1E-07							.29E-08							
11	18	5.46E-08							.77E-08							
12	20	0							0							
13																
14		1							1.7							
15	0	-3.1E-07							-2.6E-07							
16	2	-3E-07							-2.6E-07							
17	4	-2.9E-07							-2.2E-07							
18	6	-2.7E-07							-1.8E-07							
19	8	-2.4E-07							-1.5E-07							
20	10	-2.1E-07							-1.3E-07							
21	12	-1.7E-07							-1.2E-07							
22	14	-1.3E-07							-9.7E-08							
23	16	-9E-08							-6.3E-08							
24	18	-4.5E-08							-2.4E-08							
25	20	0							0							
26																
27		1							1.7							
28	0	1.05E-23							-3.1E-07							
29	2	1.17E-23							-2.2E-07							
30	4	5.06E-23							-1.1E-07							
31	6	-4.8E-24							-1.8E-08							
32	8	-3E-23							.85E-08							
33	10	-1.9E-23							.24E-08							
34	12	-3.1E-25	7.7E-09	1.71E-08	2.75E-08	3.86E-08	4.99E-08	6.11E-08	7.19E-08	8.2E-08	9.11E-08	9.92E-08	1.06E-07	1.11E-07	1.15E-07	1.
35	14	-5E-23	9.82E-09	1.97E-08	2.98E-08	4.01E-08	5.02E-08	6E-08	6.93E-08	7.78E-08	8.55E-08	9.21E-08	9.76E-08	1.02E-07	1.05E-07	1.

Average: 0.462356827 Count: 611 Sum: 282.5000214

Fig. 3.13 Spreadsheet “Ground Vib, Vertical”

Others

TLEM1_2.exe and TLEMz.exe create total 31 output data files in the same folder where both TLEM1_2.exe and TLEMz.exe exist.



deflec_Pyz.dat
deflec_Vyz.dat
✓eff_motionz.dat
react_Pyz.dat
react_Vyz.dat
✓space_dspz.dat
✓top_flxz.dat
✓top_stfz.dat
deflec_Fr.dat
deflec_M.dat
deflec_Px.dat
deflec_Vx.dat
deflec_Vz.dat
✓eff_motion.dat
react_Fr.dat
react_M.dat

react_Px.dat
react_Vx.dat
react_Vz.dat
✓space_dsp.dat
stf_rock.dat
✓top_flx.dat
✓top_stf.dat
✓vib_mode.dat
EQ_STFz.dat
equi_stiff.dat
ARRANGE.dat
FREQ.dat
LAYER.dat
PILEPRM.dat
SDISP.dat
TLEM_Output.xlsm

TLEM1_3.xlsm
PLPRM.exe
TLEMz.exe
TLEM1_2.exe
Manuals
source

TLEM_Output.xlms has only 6 spreadsheets for the 9 data files with check marks ✓, because the others can be less frequently used in practice. Details of the other files are available in (Konagai K., 2000).

References:

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