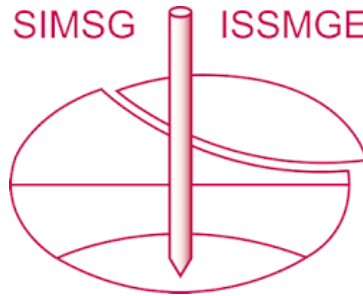


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The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 - 20 June 2019.

Developing and optimizing regional G_0 correlations using SCPT_u data

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ABSTRACT: This paper presents a methodology for developing and optimizing regional small-strain shear modulus G_0 correlations based on SCPT_u data. The intent is to develop G_0 correlations that make use of conventional CPT_u data (q_c , f_s , u_2) so they may be applied to other similar sites where no seismic geophysical testing has been undertaken. Regional correlations are developed for alluvial and marine depositional environments, based on high quality SCPT_u data that has been undertaken at 15 sites across Christchurch, New Zealand. The regional correlations are validated by undertaking blind predictions of G_0 profiles on five other sites in the study region where high quality SCPT_u data is also available. Comparisons are made between measurements from the seismic geophysical testing, the G_0 profiles estimated by the proposed regional correlations and by other empirical correlations. Comments are made on the usefulness of the proposed method.

1 INTRODUCTION

An accompanying paper presents a methodology for developing and optimizing site-specific small-strain shear modulus G_0 correlations using SCPT_u data (Barounis et al. 2019). This paper relies on the methodology presented in the accompanying paper in order to develop the regional G_0 correlations. The intent is to develop and optimize G_0 correlations based on SCPT_u data that can be applied to conventional CPT_u data. These correlations can then utilize more prevalent conventional CPT_u data for estimating G_0 and small-strain shear wave velocity V_s profiles for low importance level projects on other sites in the region, without the need to undertake seismic geophysical testing. Regional correlations are developed for Christchurch, New Zealand, based on high quality seismic geophysical testing that has been undertaken at 15 sites dispersed across the region. A correlation validation process is undertaken by making blind predictions of G_0 profiles on five other sites in the study region. Comparisons are made between direct measurements from the seismic geophysical testing, and the G_0 profiles estimated by the proposed regional correlations and by other empirical correlations.

2 THEORETICAL BACKGROUND OF THE PROPOSED METHODOLOGY

The site-specific G_0 correlation for normally consolidated saturated soil takes the form of Equation 1 (Barounis et al. 2019):

$$G_0 = A \left(\frac{e}{\left(\frac{2\sigma'_v}{303} \right)^m} \right)^{-x} \quad (1)$$

where G_0 = small-strain shear modulus; A = a material coefficient; e = in-situ void ratio; σ'_v = vertical effective overburden pressure; m = an assumed empirical model fitting parameter

(input); x = the best-fit empirical correlation parameter (output). Another important empirical parameter is presented in Equation 2 below:

$$n = mx \quad (2)$$

where n = an empirical model fitting parameter (output).

3 CASE STUDY REGION AND SITE SELECTION REQUIREMENTS

SCPT_u data is required in order to develop site-specific and regional G_0 correlations in the format that are presented in this paper. Several other requirements for the selection of case study sites in the study region must also be satisfied, including:

- High quality SCPT_u data must be dispersed across the study region
- A relatively shallow groundwater table must be present throughout the study region
- Boreholes have been undertaken in close proximity to the SCPT_u to verify soil profiles and groundwater conditions

The regional G_0 correlations developed in this paper are based on high quality SCPT_u data that has been undertaken at 15 randomly selected sites across Christchurch, New Zealand. The study region has an approximate area of 120km², which equates to an average testing frequency of one SCPT_u per 8km². The level of confidence in the regional shear wave velocity correlations will depend on the number of sites included in the development of the correlations and the variability of ground conditions throughout the region. The correlations that are developed for the region must also be validated by estimating the G_0 profiles on other similar sites in the study region where seismic geophysical testing has been undertaken to prove they are sufficiently accurate.

Figure 1 indicates the location of all 20 sites involved in this study: the 15 case study sites that have been used to develop the regional G_0 correlations (highlighted red); and the five other randomly selected case study sites that were used to validate the correlations (highlighted blue). All sites have been superimposed on the GNS Geology of the Christchurch Urban Area: Geological Map 1 (GNS 1992). It can be seen that the majority of sites are located in alluvial and marine depositional environments. Several sites are located on fixed and semi-fixed sand dunes and beaches. Site 5 is located near a drained estuary and Site 17 is located in the vicinity of a drained peat swamp.

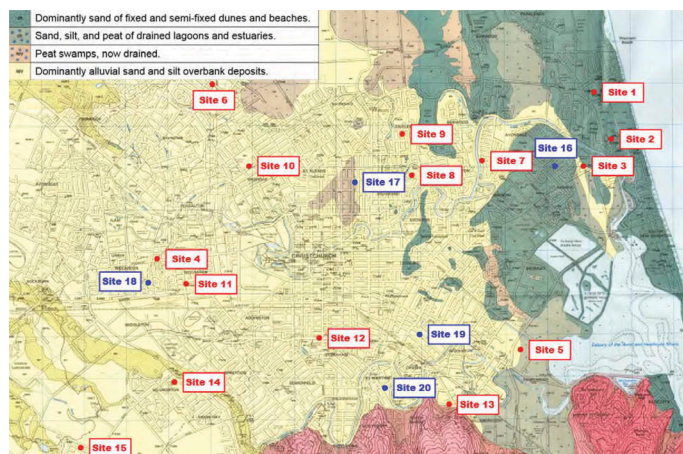


Figure 1. GNS Geology of the Christchurch Urban Area (Geological Map 1, 1992) with 20 case study sites superimposed.

4 DEVELOPING AND OPTIMIZING REGIONAL G_0 CORRELATIONS

4.1 *Developing and optimizing site-specific G_0 correlations*

The methodology for developing and optimizing site-specific G_0 correlations from $SCPT_u$ data (Barounis et al. 2019) was applied to Sites 1-15 (refer to Figure 1) and the results are summarized in Table 1 below.

Soil conditions encountered across the region include organic soil, clays, silts, sands, gravels and their mixtures. Soil layers that have significant microstructure (Robertson 2016) were encountered at Sites 4 and 6. Sites 4 and 6 have similar soil configurations that include soft/ loose soil layers overlying dense sandy gravels that have significant microstructure ($K^*_G > 330$). The presence of these dense sandy gravel layers at these sites creates a marked stiffness contrast in the G_0 profiles that are not present at the other sites.

Table 1 presents the optimal empirical model fitting parameters from Equations 1 and 2 (A, m, x and n) for each site to show the variability in these parameters across a wide variety of soil types and soil layer configurations. The dense sandy gravel layers that have significant microstructure are noted to have a marked effect on the empirical model fitting parameters. The R^2 values indicate a strong G_0 correlation can be developed for most sites, with the exception of Sites 13 and 15. There is relatively poor agreement between the CPT_u data and the seismic geophysical testing data at Site 13, particularly below 17m depth. The $SCPT_u$ at Site 15 experienced refusal at approximately 7.5m below the ground surface. The shallow refusal limited the amount of data points obtained within the fully saturated soil, and the overall trend between the V_s profile and the CPT_u data is poor, so the majority of data points were omitted from the correlation.

4.2 *Developing and optimizing regional G_0 correlations*

The regional G_0 correlations are developed using a similar method to the site-specific G_0 correlation; however, the data must be carefully interpreted to identify any unique site-specific influences on the G_0 correlations. Key influences to consider may include soil profiles with large stiffness contrasts, soil layering configurations that are vastly different to other sites in the region, the presence of soil layers with significant microstructure, or over-consolidated soil layers.

The measured G_0 from seismic geophysical testing is plotted against the stress-normalized void ratio in Figures 2 and 3 below. It can be seen there are two distinct G_0 correlations that can be developed from the data points from the 15 case study site. The key reason for the

Table 1. Summary of parameters for each of the assumed empirical models

Site #	Soil Conditions	A	m	x	n	R^2
1	Sand & silty sand	36.39	0.21	2.31	0.48	0.97
2	Sand & silty sand	38.73	0.34	2.01	0.67	0.93
3	Sand & silty sand	66.51	0.52	1.18	0.61	0.93
4	Peat, clays, silts and sands overlying gravels	100.51	0.36	2.27	0.82	0.93
5	Sand & silty sand	33.30	0.10	2.10	0.20	0.93
6	Peat, clays, silts and sands overlying gravels	100.76	0.30	2.19	0.66	0.89
7	Sand & silty sand	89.38	1.90	0.51	0.96	0.98
8	Sand & silty sand	69.25	0.55	0.69	0.38	0.89
9	Sand & silty sand	74.00	1.43	0.42	0.60	0.96
10	Mixture of clays, silts and sands	9.37	0.46	1.25	0.58	0.96
11	Mixture of clays, silts, sands and gravels	65.34	0.49	1.12	0.55	0.95
12	Mixture of clays, silts, sands and gravels	60.65	0.75	0.86	0.65	0.91
13	Mixture of clays, silts and sands	55.85	0.50	1.43	0.71	0.85*
14	Mixture of clays, silts and sands	55.12	0.05	2.15	0.11	0.89
15	Mixture of clays, silts, sands and gravels	74.95	0.50	0.86	0.43	1.00**

* Generally a poor correlation between V_s profile and CPT_u data

** Not a legitimate site-specific correlation due to there being only two valid data points

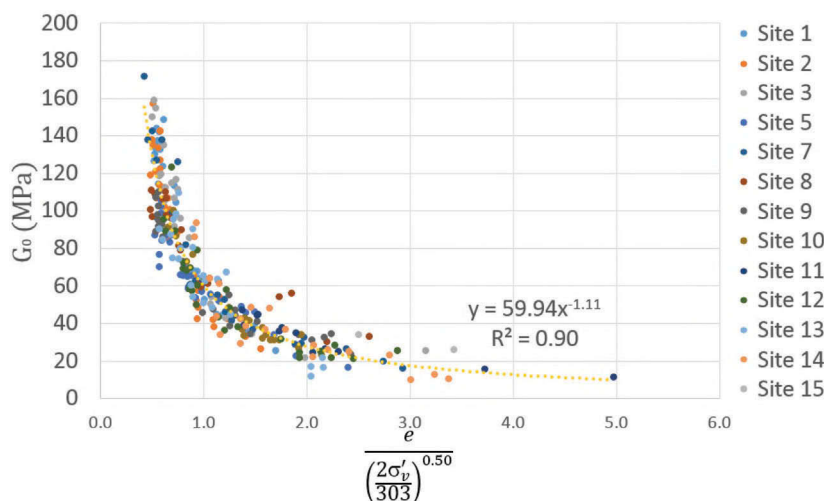


Figure 2. Regional G_0 correlation for Christchurch sites with soils that do not have significant microstructure.

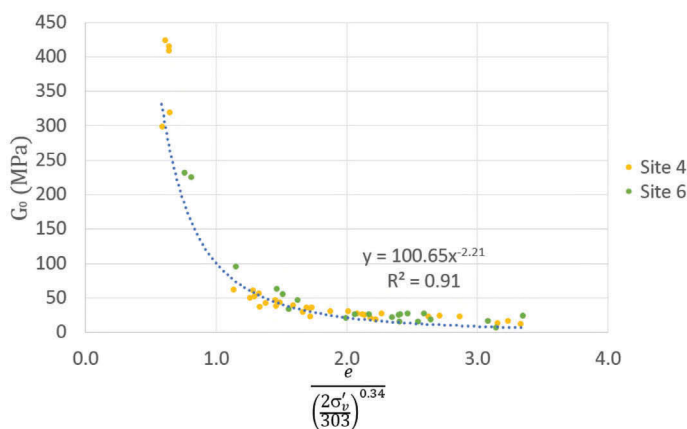


Figure 3. Regional G_0 correlation for Christchurch sites with soft/loose soil overlying dense sandy gravel layers with significant microstructure.

difference in the two correlations is there are dense sandy gravel layers that have significant microstructure at Sites 4 and 6. This means that one correlation will be useful for characterizing sites with soft/loose soil overlying a dense sandy gravel layer; whereas, a different correlation will be more appropriate for characterizing site where the dense sandy gravel layer is not encountered.

As a result, Equation 3 is relates to the majority of sites in Christchurch, and Equation 4 relates to those sites that have soft/loose soil overlying a dense sandy gravel layers that has significant microstructure. The optimization plots for both correlations are shown in Figure 4 below.

$$G_0 = 59.94 \left(\frac{e}{\left(\frac{2\sigma'_v}{303} \right)^{0.50}} \right)^{-1.11} \quad (3)$$

$$G_0 = 100.65 \left(\frac{e}{\left(\frac{2\sigma'_v}{303} \right)^{0.34}} \right)^{-2.21} \quad (4)$$

4.3 Indicative site characteristics for regional G_0 correlations

Figure 5 shows two different SBT_n and G_0 profiles for soil conditions that are representative of those that have been encountered when developing the two recommended regional G_0 correlations (Equations 3 and 4).

4.4 Validating the regional G_0 correlations

In order to validate the regional correlations, these correlations were used to make blind predictions of the G_0 profiles for five other sites in the region. The blind predictions were carried out for these five sites using the most appropriate of the two recommended regional correlations in Equations 3 and 4. To replicate conditions for low-risk projects where no seismic geophysical testing would be available, the seismic geophysical data was not reviewed prior to estimating the G_0 profile for each of these five sites, leaving the conventional CPT_u data and borehole results as the only site-specific information utilised to select the most appropriate regional correlation for estimating the G_0 profile. The intent of this procedure is to validate the regional correlations as a standalone CPT -based method, without the need to undertake site-specific seismic geophysical testing for low-risk projects.

Based on the available CPT_u and borehole information, Equation 3 was considered to be the most appropriate for estimating the G_0 profile for Sites 16, 17, 19 and 20. Equation 4 was selected for estimating the G_0 profile at Site 18 due to the presence of soft/loose shallow soil overlying a dense sandy gravel layer.

Blind predictions of the G_0 profiles for each of these five sites are shown in Figures 6–10 below. The G_0 profile obtained from the seismic geophysical testing and other empirical correlations are also shown on these figures for the purposes of validating the proposed methodology; although, it should again be noted these did not influence the selection of the most appropriate regional correlation to use for these sites.

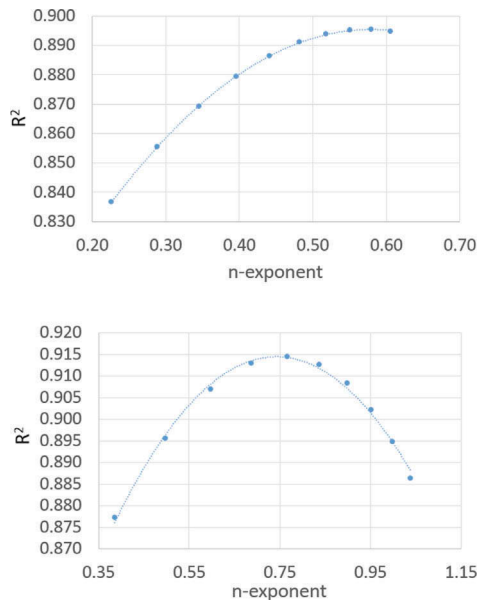


Figure 4. Optimization plots for Equation 3 (top) and Equation 4 (bottom).

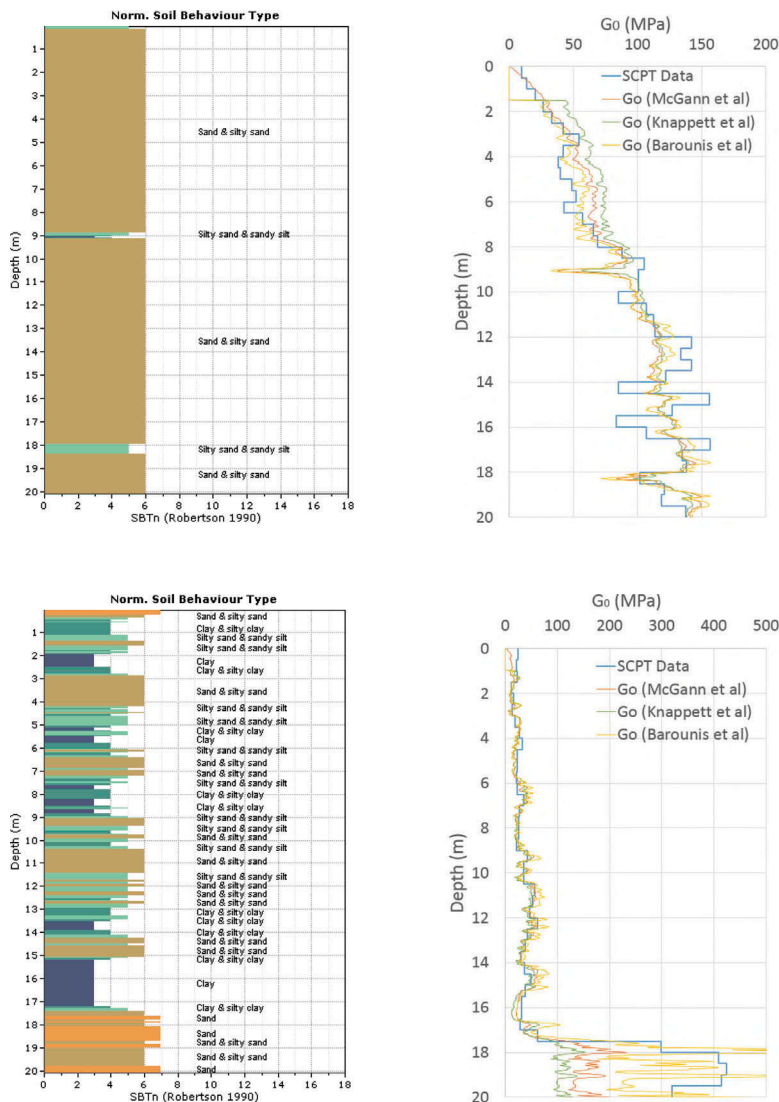


Figure 5. Indicative SBT_n for 'Equation 3' sites (left – previous page), indicative G_0 profile for 'Equation 3' sites (right – previous page), indicative SBT_n for 'Equation 4' sites (left – current page), and indicative G_0 profile for 'Equation 4' sites (right – current page).

The percentage residual error plot shown in Figure 11 confirms that all methods of estimating shear wave velocity are working well for Site 20. Average residual errors of less than 10% are produced by all methods for the fully saturated soil. Excluding the questionable data observed in some layers of the soil profile, there are very few instances where the methods are producing residual errors in excess of 20%, and the largest errors are generally produced near significant transition layers in the soil profile. All three correlations are performing similarly well for Site 20.

It can be seen that the two recommended regional G_0 correlations are capturing the measured G_0 profile with a relatively high degree of accuracy and are performing similarly to other empirical correlations. It is considered that the regional correlation presented in Equation 3 has been validated for use on other sites in the region where there are no soil layers that have significant microstructure.

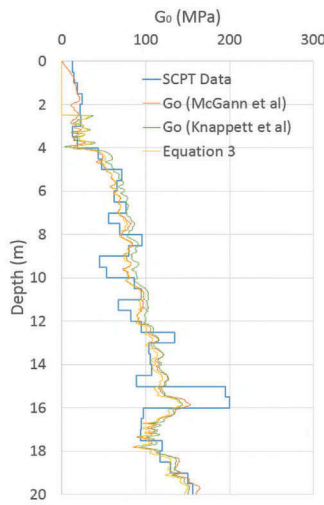


Figure 6. G_0 profile for Site 16

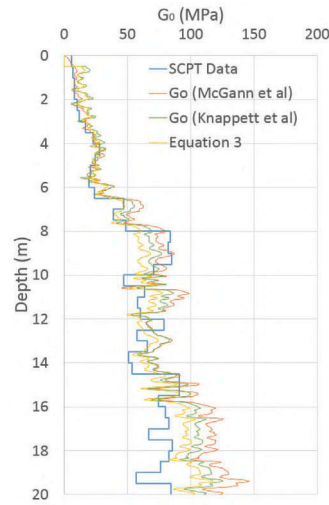


Figure 7. G_0 profile for Site 17

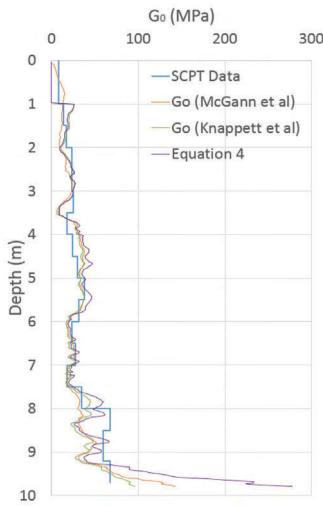


Figure 8. G_0 profile for Site 18

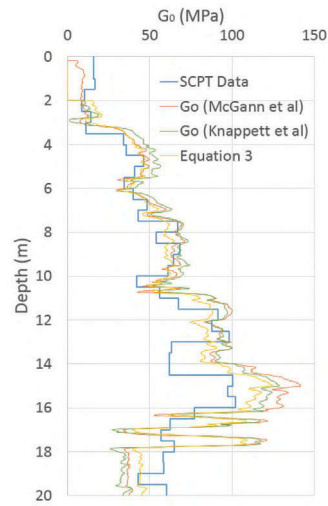


Figure 9. G_0 profile for Site 19

Unfortunately, the $SCPT_u$ at Site 18 experienced refusal prior to obtaining any G_0 measurement in the dense sandy gravel layer. As a result, the regional G_0 correlation presented in Equation 4 for sites with dense gravels that have significant microstructure could not be validated based on this dataset. It is recommended that Equation 4 is validated at another similar site in the region prior to it being adopted for use on other similar sites without the need to undertake seismic geophysical testing.

5 CONCLUSION

This paper has presented a methodology for developing and optimizing regional G_0 correlations based on $SCPT_u$ data. Two regional G_0 correlations have been developed based on high quality $SCPT_u$ data spread across 15 sites in the study region. Equation 3 defines the

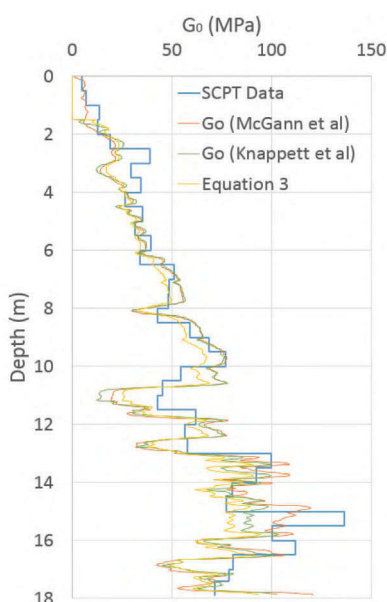


Figure 10. G_0 profile for Site 20

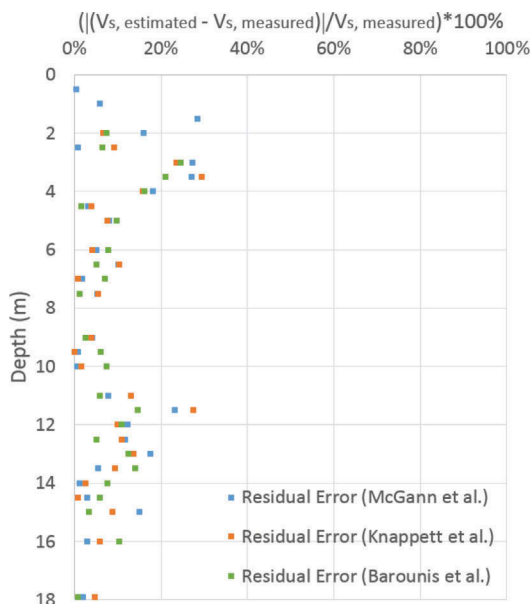


Figure 11. Percentage residual error for Site 20

regional G_0 correlation for sites with soil layers that do not have significant microstructure. Equation 4 defines the regional G_0 correlation for sites that have loose/soft soil overlying a dense sandy gravel layer that has significant microstructure.

Based on blind predictions undertaken at five other sites in the study region, Equation 3 has been validated for use on other similar sites for low risk projects without the need to undertake seismic geophysical testing. Unfortunately, Equation 4 has not been validated due to the refusal depth of the SCPT_u at Site 18; therefore, it is recommended that this regional correlation is validated on another similar site in the study region prior to it being adopted for use without the need to undertake seismic geophysical testing.

The method could be modified and extended to also make use of DMT data, or instead use SDMT as the basis for developing the G_0 correlation; however, further research is required to validate this.

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