for which there is a significant empirical database (e.g. refer to Parkes *et al.*, 2018)).

At the other extreme, if the pile head is approaching a 'fixed' condition, then most of the applied lateral loading tends to be converted into a 'push–pull' action (that is, the applied lateral load is resisted by vertical pile resistance (compression and tension) across the group), which then reduces the practical effects of nonlinearity. If linear elastic analyses are being used, then it is recommended that a simple set of checks are implemented: first, the sensitivity of pile bending moments and group deformation to variations in shallow ground stiffness is checked (i.e. within a depth equal to the 'critical pile length' for lateral loading, L_c, typically the upper 6d to 10d, where d is the pile diameter), perhaps by doubling and halving ground stiffness compared with the design assumption; second, the structural demands are considered in the context of local yield of the pile material (e.g. concrete 'cracking moment').

For critical situations, specialist advice should be sought and more sophisticated nonlinear analyses may be required. Hardy and O'Brien (2006) discussed the influence of ground stiffness nonlinearity on the predictions of bending moment in pile groups subjected to horizontal loads. For single piles, back-analysis of vertical and lateral load tests highlighted the significant influence of nonlinearity on lateral pile performance (across the working load range, 'elastic' secant stiffness reduced to about half its initial value for vertical loading, whereas for horizontal loading it reduced to less than 15% of its initial value). **Figure 55.32** shows that for a medium-size pile group, the pile bending moments can be sensitive to the soil constitutive model (hyperbolic or linear elastic) and, for the linear elastic model, the magnitude of the selected moduli. If the design is substantially influenced by lateral load effects, then nonlinear analyses should be implemented (Mandolini *et al.*, 2005; O'Brien, 2007). These analyses may require specialist input and guidance, although software such as REPUTE includes a hyperbolic model which is quick to use for suitably experienced practitioners.

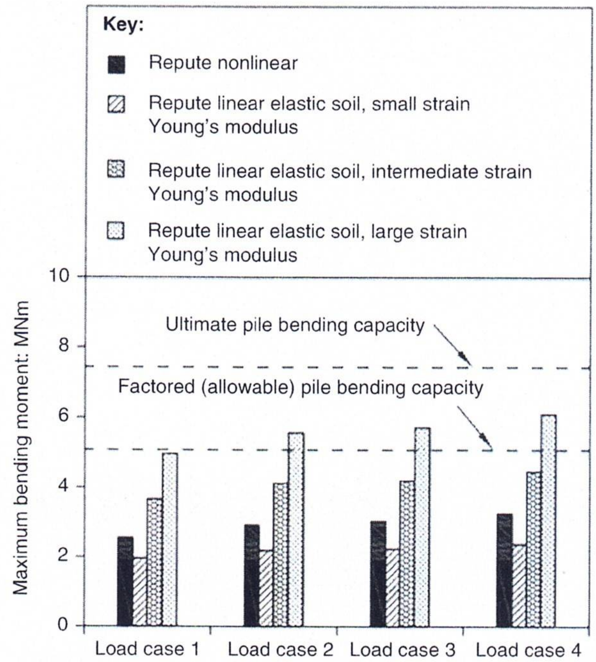

Figure 55.32 Influence of soil model and selected Young's modulus on the peak bending moment under horizontal loading (Reproduced from Hardy and O'Brien, 2006)

55.9.5 Ground stiffness characterisation for pile groups

When considering the selection of input parameters for pile-group analysis, and, in particular, comparing single-pile with group performance, it is helpful to consider the different zones of ground around a pile or pile group that will influence behaviour (**Figures 55.33** and **55.34**), and the relevant information that will be needed for making decisions. Five separate zones, and associated ground stiffness moduli, can affect behaviour.

- The stiffness of the soil or rock close to the pile shaft: this zone will strongly influence the settlement of a single pile at typical working loads. It will be strongly affected by the construction process (remoulding and horizontal stress changes), either due to pile boring or pile driving.
- The stiffness of the soil or rock at the pile toe: this zone is dominated by the construction process and is generally far more sensitive to the construction process than shaft stiffness. Base stiffness will be crucially important for end-bearing piles; however, for many piles (which often gain significant shaft resistance) the base stiffness only becomes influential at low factors of safety. For driven piles the base stiffness tends to be relatively high compared with the original ground stiffness. For bored piles, the base stiffness will tend to be lower, sometimes much lower, than the original ground stiffness and will be highly dependent on factors such as groundwater inflows, debris at the pile toe and the effectiveness of any base-cleaning activities (Fleming, 1992).
- The stiffness of the ground close to the ground surface: this can strongly affect pile behaviour under horizontal loading, especially for single piles and small pile groups. Ground investigations frequently overlook the characterisation of this zone, and it can be extremely variable. Also, site redevelopment (excavation and filling) will often change the nature of this zone. Pile concrete stiffness under lateral loads will tend to be lower (due to yield, creep and cracking) than that for compression.
- Ground stiffness between the piles: this zone has a dominant influence on pile-group settlement. This zone will not be significantly affected by construction activities. As noted earlier, the relevant modulus, for linear elastic analysis, will be close to the very small strain stiffness of the soil or rock, especially for medium and large pile groups.